unit

20 C

Photosynthesis and Cellular Respiration

For life to continue on Earth, two conditions must be met. First, matter must be continuously cycled. With few exceptions, the number of atoms on Earth is unchanging. Although the atoms may be rearranged into new molecules, matter is continuously exchanged between plants, animals, fungi, and microorganisms.

The second condition for life on Earth is a supply of energy. Solar energy supplies almost all life on Earth. Plants are the key to keeping the energy flowing. These photoautotrophs absorb carbon dioxide, water, and radiant energy from the environment and, through photosynthesis, transform these components into energy-rich sugars and oxygen gas. Then, through aerobic respiration, they convert the energy stored in these sugars and oxygen into the energy of ATP.

Heterotrophs, such as animals, fungi, and some protists, obtain nutrients from their environment by eating plants, animals, or both. Like plants, heterotrophs obtain energy in the form of ATP by cellular respiration in which large food molecules are broken down and carbon dioxide and water are returned to the environment. In this unit, you will investigate these transformations and exchanges of energy within our living world.

As you progress through the unit, think about these focusing questions:

- How does light energy from the environment enter living systems?
- How is the energy from light used to synthesize organic matter?
- How is the energy in organic matter released for use by living systems?
- How do humans in their applications of technologies impact photosynthesis and cellular respiration?

UNIT 20 C PERFORMANCE TASK

Student Aquarist

Ecosystems must maintain a delicate balance in order to remain healthy. How do factors such as temperature, light conditions, dissolved oxygen, and dissolved carbon dioxide affect the metabolic health of the organisms within an ecosystem? At the end of this unit, you may apply your skills and knowledge to complete this Performance Task.

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GENERAL OUTCOMES

In this unit, you will

- relate photosynthesis to storage of energy in compounds
- explain the role of cellular respiration in releasing potential energy from organic compounds

Unit 20 C
Photosynthesis and Cellular Respiration

ARE YOU READY?

Prerequisites

Concepts
- organisms, cells, tissues, organ systems
- cellular structures and functions
- passive and active transport of matter

Skills
- use instruments effectively and accurately for collecting data

You can review prerequisite concepts and skills on the Nelson Web site and in the Appendices.

A Unit Pre-Test is also available online.

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These questions will help you find out what you already know, and what you need to review, before you continue with this unit.

Knowledge

1. Match the following names and functions to the labelled components of the cells in **Figure 1** (one name and one function per label).

   Names: *cell membrane, nucleus, vacuole, mitochondrion, endoplasmic reticulum, Golgi apparatus, chloroplast, cell wall, flagellum*

   Functions: *energy conversion, protein storage, protection, material transport within the cell, overall control, food production, water and nutrient storage, controlled entry and exit from cell, locomotion*

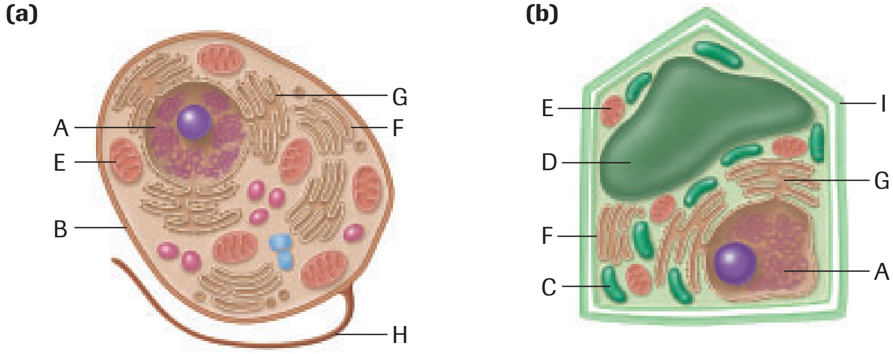

Figure 1
(a) A generalized animal cell; **(b)** A generalized plant cell

2. **Figures 2** and **3** show two processes that move materials into and out of cells.
   (a) What process is represented by **Figure 2**?
   (b) What process is represented by **Figure 3**?
   (c) Name the structure labelled "A" in **Figure 3**.
   (d) What is the substance that passes through structure A in **Figure 3**?

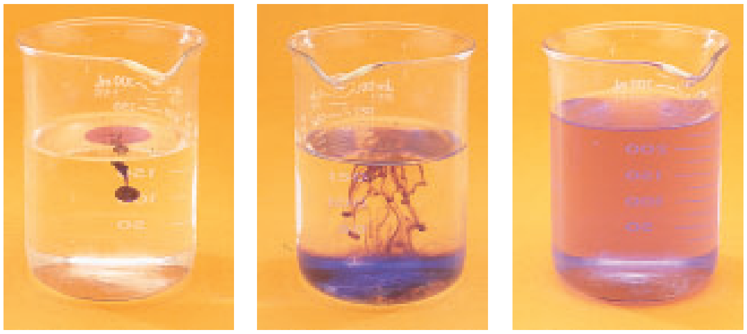

Figure 2

Figure 3

3. Compare passive transport by diffusion and osmosis with active transport in terms of (a) concentration gradients, (b) energy inputs, and (c) equilibrium and protein carrier molecules.

4. Match the following names to the labelled components of the leaf structure in **Figure 4** (one name per label).

   Names: *epidermis, guard cells, palisade tissue, spongy tissue, phloem, xylem, vascular tissue*

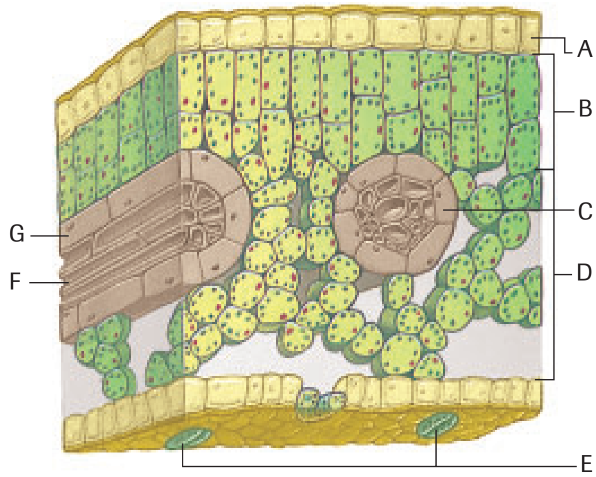

Figure 4
A typical leaf structure

5. **Figure 5** is a wet mount of onion cells viewed under medium power in a compound light microscope.
   (a) What might be the cause of the dark circles in **Figure 5**?
   (b) How could you avoid forming the circles?

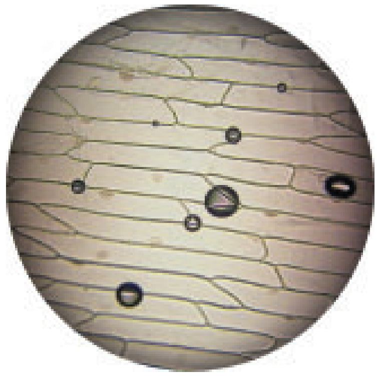

Figure 5
A wet mount of onion cells

Skills

6. Examine the following chemical equation:

CH_4	+	$2\ O_2$	→	CO_2	+	H_2O
methane		oxygen		carbon dioxide		water

   Which of the reactants is a compound? Provide reasons for your answer.

7. Match the following parts of the compound light microscope to the labels in **Figure 6**.

   Microscope parts: *arm, ocular lens, coarse-adjustment knob, stage, fine-adjustment knob, base, condenser, objective lens, revolving nosepiece, stage clips, light source*

8. Place the following steps in the correct order for viewing a slide through a compound light microscope.
   (a) Rotate the nosepiece to the medium-power objective lens.
   (b) Use the fine-adjustment knob to bring the image into focus.
   (c) Place the slide on the stage and hold it in place with clips.
   (d) Use the coarse-adjustment knob to bring the low-power objective lens close to the slide.
   (e) Make sure the low-power objective lens is in place.

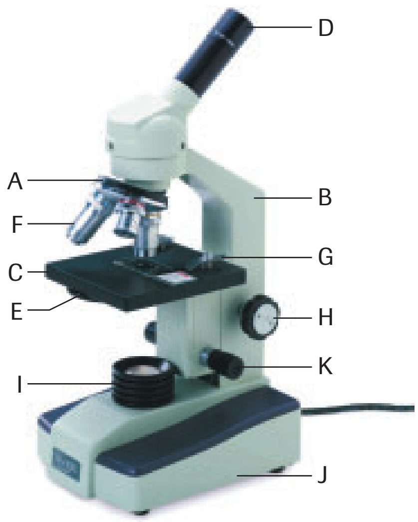

Figure 6
A compound light microscope

chapter 6

Photosynthesis

In this chapter

Exploration: Global Photosynthesis in Action

Mini Investigation: Photosynthesis and Light

Investigation 6.1: Separating Plant Pigments from Leaves

Case Study: Using Satellite and Airborne Technology to Monitor Photosynthesis and Productivity

Chemistry Connection: Energy

Web Activity: Dr. Rudolph Arthur Marcus

Explore an Issue: Harnessing Light Energy

Investigation 6.2: How Does Carbon Dioxide Concentration Affect the Rate of Photosynthesis?

Web Activity: Factors Affecting Photosynthesis

Career Connection: Nursery Operator

Photosynthesis is the process that converts energy from the Sun into chemical energy that is used by living cells. Photosynthesis occurs in a variety of organisms, but most notably in plants and certain groups of bacteria. The most obvious of these are the large land plants, but the world's oceans are also home to vast quantities of photosynthesizing microorganisms (**Figure 1** on the next page). All of these organisms convert carbon dioxide, $CO_2(g)$, into organic molecules using the light energy captured by chlorophyll.

From a human perspective, photosynthesis is the most important large-scale chemical process on Earth. We are completely dependent on photosynthesis for all the food we eat and the oxygen we breathe. In addition, all organic materials are constructed using the molecular building blocks and the energy supplied by photosynthesis. Therefore, we also rely on photosynthesis for things such as wood, paper, cotton, drugs, and fossil fuels.

As the human population grows and our rates of consumption grow, we become increasingly dependent on vast quantities of photosynthesis products. Recent estimates suggest that humans now consume, either directly or indirectly, close to 40 % of the net primary production of Earth's entire land surface. In other words, over one-third of the yearly production of all of Earth's terrestrial plants is used to meet human demands.

STARTING Points

Answer these questions as best you can with your current knowledge. Then, using the concepts and skills you have learned, you will revise your answers at the end of the chapter.

1. (a) Write the overall equation for photosynthesis.
   (b) Do the O_2 molecules produced in photosynthesis come from CO_2 or H_2O or both?
   (c) What is the purpose of water in photosynthesis?
2. Why are deciduous leaves green in the summer and yellow in the fall?
3. What does *carbon fixation* mean?
4. The process of photosynthesis requires energy in the form of ATP. How do plants obtain ATP for photosynthesis?
5. How are the processes of photosynthesis and cellular respiration dependent on each other?

Figure 1
Photosynthesizing organisms live in oceans, lakes, streams, and rivers, as well as on land.

Exploration — *Global Photosynthesis in Action*

Earth is a dynamic planet of land and water. The seasons are accompanied by changing temperatures and levels of solar radiation—factors that dramatically influence the distribution and activity of photosynthesizing organisms.

Recent technological developments enable us to monitor such changes with great precision. In this Exploration, you will view an animation of biosphere data gathered over six years as part of the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) Project. In the animation, areas of high plant life on land are shown in dark green, while areas of low plant life are shown in tan. In the oceans, areas of high active photosynthesis by phytoplankton are shown in red, and areas of lowest activity are shown in blue and purple (**Figure 2**).

(a) Generate a hypothesis to describe the overall pattern you expect to see on the land surface, and a hypothesis to describe what you expect to see in the oceans. Where and when do you think land plants and marine phytoplankton activity will peak?

(b) After recording your hypotheses, go to the Nelson Web site and follow the links to view the animation sequence.

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(c) Describe the patterns of changes you see over the six-year period.

(d) Note any surprises you observe. Was photosynthesis most active where you expected it to be?

(e) Suggest possible explanations to account for the patterns you witnessed on the land environment and in the marine environment.

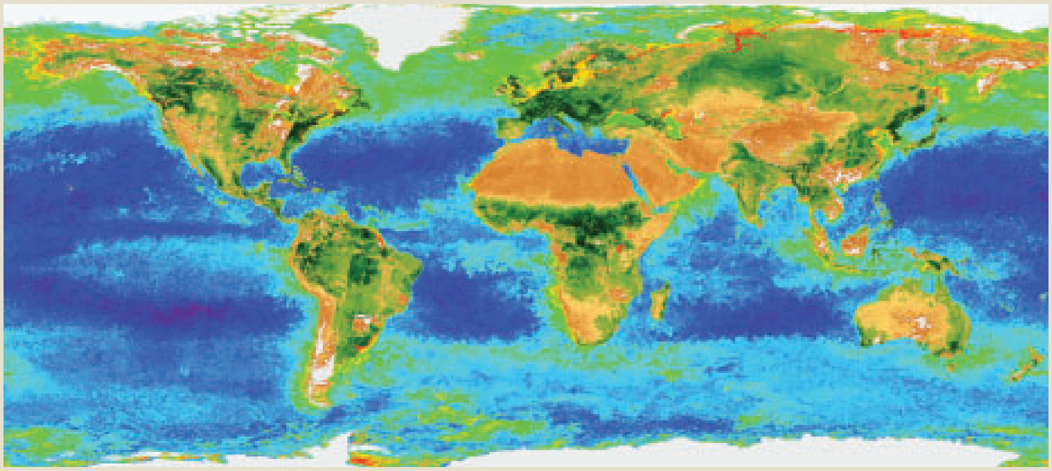

Figure 2
SeaWiFS image of global photosynthesis activity

6.1 Chloroplasts and Photosynthetic Pigments

photon a packet of light

Light is a type of electromagnetic radiation (EMR). Many forms of electromagnetic radiation are familiar to us including X-rays, microwaves, and radio waves. All EMR occurs in the form of individual packets of energy called **photons**. Each photon corresponds to a small unit of energy of a particular wavelength (**Figure 1(a)**). Photons with short wavelengths have high energy and those with long wavelengths have low energy.

Light from the Sun is a mixture of different wavelengths. When passed through a transparent prism in an instrument called a spectroscope, the different wavelengths separate from one another according to their energies, forming the electromagnetic spectrum (**Figure 1(b)**). Most of the spectrum is invisible to humans, being either in the radio, infrared, or ultraviolet range, but a narrow band, from a wavelength of 380 nm (violet light) to 750 nm (red light), forms the visible part of the spectrum.

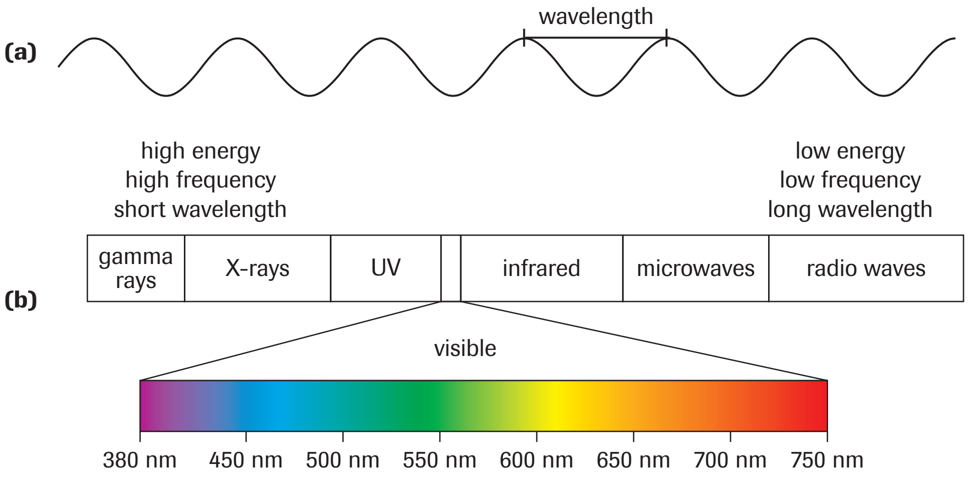

Figure 1
(a) Light is a form of electromagnetic radiation that travels as waves. One wavelength corresponds to a photon.
(b) Light is the visible portion of the electromagnetic radiation spectrum. Our eyes perceive photons of different wavelengths, or energies, as different colours.

Solar energy is the ultimate source of energy for most living things. As you saw in Chapter 2, organisms do not use this energy directly. Instead, photosynthetic organisms at the first trophic level in a food web (producers) capture solar energy and then store it as chemical energy in the bonds of glucose molecules. This energy is eventually passed to other organisms in the food web. All organisms, including those that carry out photosynthesis, release the energy in glucose molecules by cellular respiration to fuel cell activities.

Recall that the process of photosynthesis can be summarized by this equation:

$$\text{carbon dioxide} + \text{water} + \text{energy} \rightarrow \text{glucose} + \text{oxygen}$$
$$CO_2(g) + H_2O(l) + \text{energy} \rightarrow C_6H_{12}O_6(s) + O_2(g)$$

This equation includes only the compounds at the beginning and end of the process of photosynthesis. You will learn more about some of the important molecules involved in photosynthesis in the rest of this chapter.

Photosynthesis occurs only in green plants and some photosynthetic micro-organisms such as algae. Special pigments in these organisms capture photons from solar energy to begin the reactions that make up the photosynthesis process.

CAREER CONNECTION

Nursery Operator

Nursery operators work with plants, growing and selling trees, shrubs, and other plants. They direct and supervise staff to plant, transplant, and feed trees and shrubs, and they also decide the appropriate environmental conditions required to grow particular plants.

Nursery operators often work outdoors on a regular basis, and their work is creative and rewarding. Find out more about this career by visiting the Nelson Web site.

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Practice

1. Name three large groups of organisms that carry out photosynthesis.
2. (a) Define *light*.
   (b) What is a photon?

mini Investigation Photosynthesis and Light

Green plants capture sunlight and transfer the energy to carbohydrates through the process of photosynthesis. When plants photosynthesize, they absorb carbon dioxide and produce oxygen. The oxygen produced is released into the environment. In this activity, you will observe the production of oxygen in photosynthesizing plant cells.

Materials: living green plants with leaves, baking soda, liquid soap or detergent, medicine dropper, water, drinking straw, 35 mm film canister with lid, 5 mL syringe, eye protection

- Add enough baking soda to barely cover the bottom of a film canister. Fill the canister with water (almost to the top), replace the lid, and shake to dissolve the baking soda.
- Remove the lid, add one small drop of liquid soap, replace the lid, and gently swirl the contents to dissolve the soap. Do not shake. The soap will help prevent static electricity.
- Use a new straw like a cookie-cutter to cut four leaf discs from a plant leaf. The leaf discs will accumulate inside the straw.

Never share straws with others. Always use a new straw. When finished using the straw, discard it in the garbage can.

- If the syringe you are using has a cap on the tip, remove the cap. Pull the plunger out of the syringe. Blow the leaf discs out of the straw and into the syringe. Replace the plunger.
- Draw 4 mL of baking-soda solution (prepared in the first two steps) into the syringe. Invert the syringe so that the tip end is pointing up. Gently push the plunger to remove the air near the tip.
- Put your finger over the syringe tip and pull the plunger. This will create a vacuum, which will pull air and oxygen from the leaf discs (**Figure 2**).

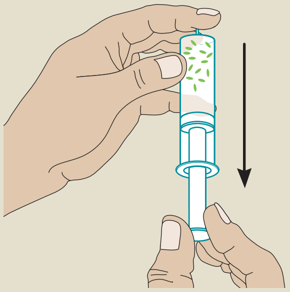

Figure 2

- Tip the end of the syringe down so that the leaf discs are in the solution. Release the plunger and remove your finger. Turn the syringe back up and tap the side repeatedly until all (or most) of the discs sink.
- Place the syringe, open end up, in bright sunlight.
- As the leaf discs photosynthesize, they will float to the top.

(a) (i) What causes the leaf discs to float to the top while they are in sunlight?
(ii) Would the discs float to the top if the syringe was kept in the dark? Explain.
(b) Why is baking soda added to the solution in the syringe?
(c) Did the leaf discs all float to the top at the same time? Explain why or why not.
(d) How could this procedure be used to investigate whether or not different colours of light cause plants to photosynthesize equally well? Design a procedure for such an experiment (include a list of materials).

Chlorophyll

Photosynthesis is carried out by a number of different organisms, including plants, algae, some protists, and cyanobacteria. These organisms all contain the green-coloured pigment called **chlorophyll**. Chlorophyll absorbs photons from solar energy and begins the process of photosynthesis. Several types of chlorophyll are found in photosynthetic organisms; chlorophyll *a* (blue-green) and chlorophyll *b* (yellow-green) are two common forms. All photosynthetic organisms use chlorophyll *a* as the primary light-absorbing pigment.

chlorophyll the light-absorbing green-coloured pigment that begins the process of photosynthesis

Chlorophylls *a* and *b* absorb photons with energies in the blue-violet and red regions of the spectrum and reflect or transmit those with wavelengths between about 500 nm and 600 nm, which our eyes see as green light. This is why most photosynthesizing organisms look green in white light. Using a sophisticated instrument called a

EXTENSION

The Action Spectrum, the Absorption Spectrum, and Photosynthesis

Listen to this Audio Clip, which explores absorption and action spectra for the primary photosynthetic pigments chlorophyll *a* and *b*.

spectrophotometer, the absorption spectrum of pigments, such as chlorophyll *a* and chlorophyll *b*, can be determined with accuracy, as **Figure 3** shows.

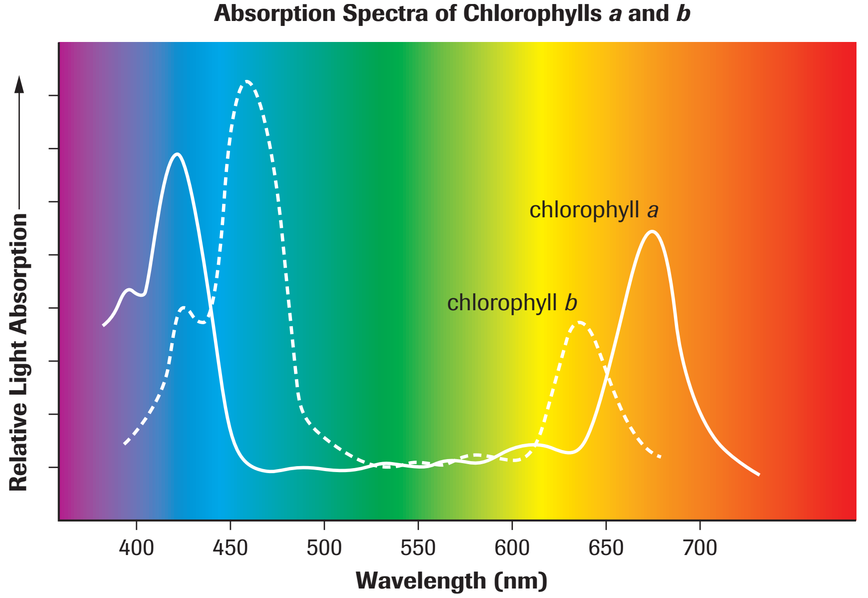

Figure 3
The absorption spectrum of chlorophyll *a* and chlorophyll *b*.

Chlorophyll *a* is the only pigment that can transfer the energy from sunlight to the reactions of photosynthesis. Chlorophyll *b* acts as an accessory pigment, absorbing photons that chlorophyll *a* absorbs poorly, or not at all. Other compounds, called carotenoids, also act as accessory pigments. These and other accessory pigments usually transfer the energy they absorb back to a molecule of chlorophyll *a*.

In spring and summer, most leaves appear green because of the high concentration of chlorophyll in the chloroplasts of leaf cells. Although the accessory pigments are also present, their colours are overwhelmed by the green light reflected by chlorophyll. With the onset of cooler autumn temperatures, plants stop producing chlorophyll molecules and disassemble those already in the leaves. This causes the yellow, red, and brown colours of autumn leaves to become visible, as **Figure 4** shows.

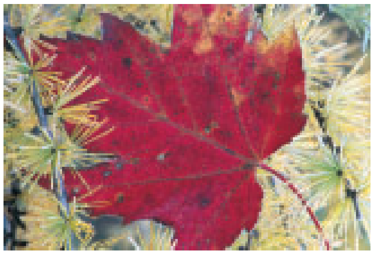

Figure 4
Autumn leaves contain less chlorophyll, so the colours of the accessory and other pigments can be seen.

Practice

3. What is the primary light absorbing pigment in all photosynthetic organisms?

4. What colour(s) of the spectrum is absorbed by chlorophyll *a* and chlorophyll *b*? What colour(s) is transmitted by these pigments?

INVESTIGATION 6.1 *Introduction*

Separating Plant Pigments from Leaves

Look at **Figure 5** with unaided eyes and determine its colour. Now look at the figure with a magnifying glass. What colours do you see? The spring and summer leaves of deciduous trees appear green in colour. Do green leaves contain only green pigments, or is there a mixture of pigments with the green variety predominating? Investigation 6.1 will help you decide.

Report Checklist

● Purpose	○ Design	● Analysis
● Problem	○ Materials	● Evaluation
○ Hypothesis	○ Procedure	○ Synthesis
● Prediction	● Evidence	

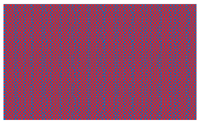

Figure 5
A colour made up of other colours.

To perform this investigation, turn to page 195.

Chloroplasts

Leaves are the primary photosynthetic organs of most plants. To undergo photosynthesis, a plant cell must contain chlorophyll, and it must be able to obtain carbon dioxide and water, and capture solar energy from its environment. Plant cells contain chloropyll within the photosynthetic membranes of discrete organelles called **chloroplasts**. Because they contain chlorophyll, chloroplasts give leaves, stems, and unripened fruit their characteristic green colour. Since chloroplasts are found only in these parts, no other structures in a plant are able to photosynthesize.

A typical plant cell chloroplast is approximately 3 μm to 8 μm in length and 2 μm to 3 μm in diameter. Chloroplasts have two limiting membranes, an outer membrane and an inner membrane (**Figure 6**). These membranes enclose an interior space filled with a protein-rich semiliquid material called **stroma**. Within the stroma, a system of membrane-bound sacs called **thylakoids** stack on top of one another to form characteristic columns called **grana**. A typical chloroplast has approximately 60 grana, each consisting of 30 to 50 thylakoids. Adjacent grana are connected to one another by unstacked thylakoids called **lamellae**. Photosynthesis occurs partly within the stroma and partly within the **thylakoid membrane**, which contains light-gathering pigment molecules and other molecules and complexes that are essential to the process. Thylakoid membranes enclose an interior (water-filled) thylakoid space called the **thylakoid lumen**. The structure of the thylakoid system within the chloroplast greatly increases the surface area of the thylakoid membrane and, therefore, also significantly increases the efficiency of photosynthesis. Chloroplasts are able to replicate, by division, independently of the cell. Starch grains and lipid droplets may also be found in chloroplasts.

chloroplast a membrane-bound organelle in green plant and algal cells that carries out photosynthesis

stroma the protein-rich semiliquid material in the interior of a chloroplast

thylakoid a system of interconnected flattened membrane sacs forming a separate compartment within the stroma of a chloroplast

grana (singular: *granum*) stacks of thylakoids

lamellae (singular: *lamella*) groups of unstacked thylakoids between grana

thylakoid membrane the photosynthetic membrane within a chloroplast that contains light-gathering pigment molecules and electron transport chains

thylakoid lumen the fluid-filled space inside a thylakoid

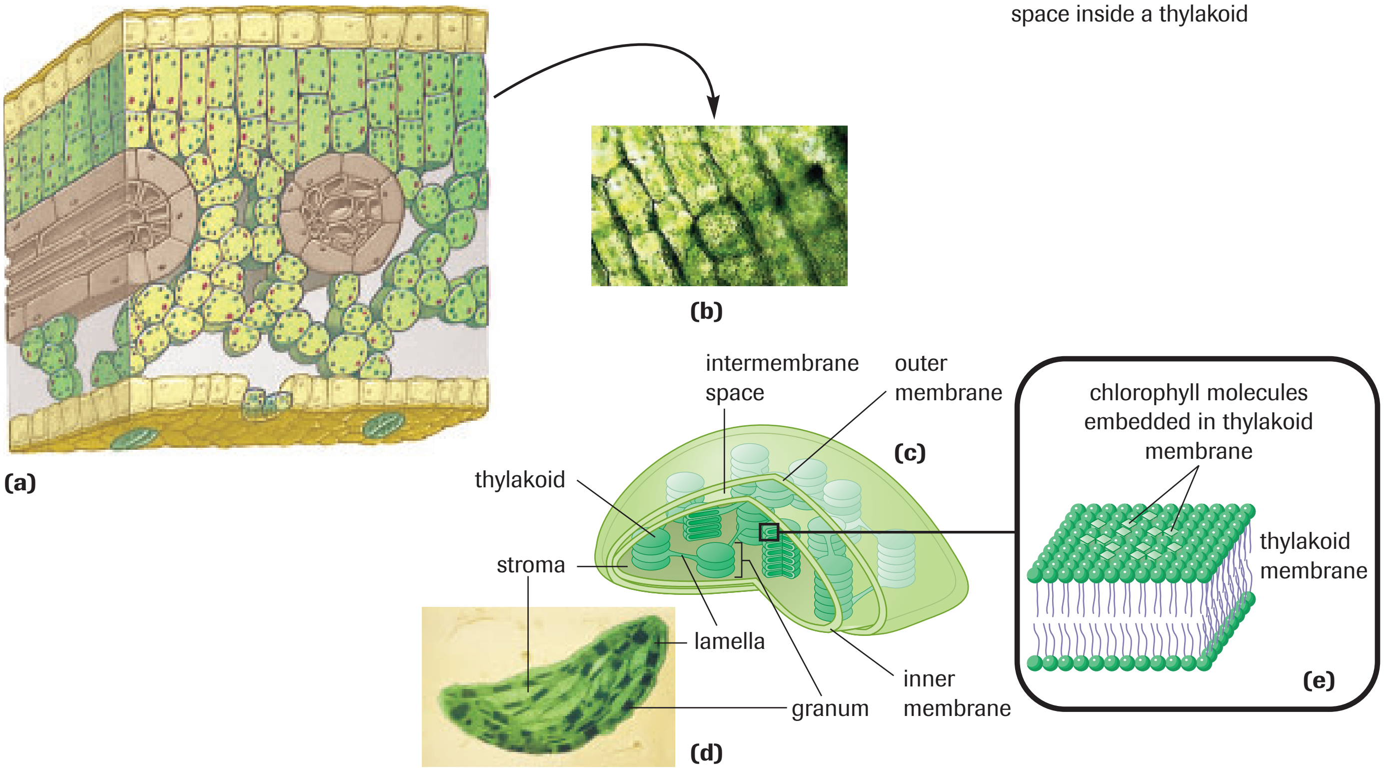

Figure 6
(a) Leaf cross section with mesophyll cells containing chloroplasts
(b) Chloroplasts within plant cells
(c) An artist's representation of a chloroplast, showing key components
(d) An electron micrograph of a chloroplast
(e) Chlorophyll molecules in the thylakoid membrane

Case Study

Using Satellite and Airborne Technology to Monitor Photosynthesis and Productivity

Healthy crop plants generally have a high chlorophyll content and a normal leaf structure. The leaves reflect green and infrared light and a small amount of red light—the red light is readily absorbed by higher concentrations of chlorophyll. In contrast, stressed or damaged plants have a lower chlorophyll content and an altered leaf structure. These changes reduce the amount of green and infrared light that is reflected. The ratio of reflected infrared light to reflected red light is an excellent indicator of plant health, and changes in this ratio are an early indication of stress conditions. These ratios form the basis of some standards, or health indexes, such as the normalized differential vegetation index (NDVI).

Farmers can assess stresses within fields using this same technology. The airborne image of fields near Altona, Manitoba (**Figure 7**) can be used in a variety of ways. The more deeply coloured red (wheat) and pink (canola) regions are healthy while the darker and duller regions have thin or missing vegetation. This image was obtained using a compact airborne spectrographic imager (CASI) instrument.

Deforestation is a global problem, with many serious consequences. In tropical countries, valuable rain forest is being destroyed to clear potentially valuable agricultural and pasture land. The loss of forests increases soil erosion, damages or destroys fisheries and wildlife habitat, and threatens water supplies. In some countries, such as Haiti, the results have been devastating, with most of the land base now completely devoid of crops or forests. Forestry is one of Canada's biggest industries and proper forest management is essential for a healthy, strong, sustainable economy. Remote sensing technology provides the best way to monitor the overall extent and health of our forest resources.

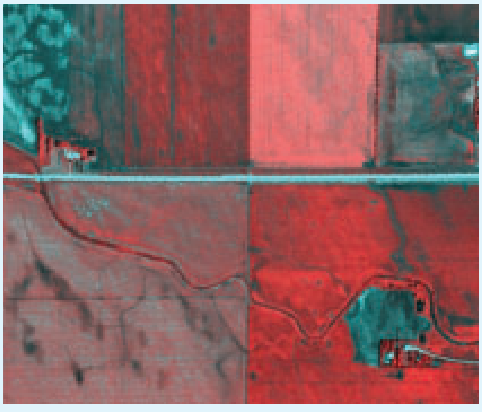

Figure 7
Remote sensing technology can provide valuable information to assess field crop health. The dark patches in the lower-left corner reveal poorly drained soil.

Clear cutting has been practised for decades in Whitecourt, Alberta. Recently however, an increasing demand for wood has accelerated this cutting and placed added stress on the land base (**Figure 8**). In addition to harvesting for the forestry industry, cuts have been made in the area for running seismic lines for oil and gas exploration.

Figure 8
This image of clear cutting near Whitecourt, Alberta reveals a highly dissected forest.

Case Study Questions

1. What symptoms of plant stress can be used to advantage by remote sensing technologies?
2. Suggest a reason why healthy plants reflect less light from the red end of the spectrum than plants under stress.
3. What ratio is used in the NDVI?
4. List some of the potentially negative consequences of excessive clear cutting. Why might Canadians be particularly concerned about the health of our forest ecosystems?
5. What advantages might the use of remote monitoring of forest management practices have over on-the-ground inspections?
6. Why are different sensor technologies often used to monitor clear cutting in tropical rain forests and temperate forests?
7. How have Aboriginal people living on First Nations and Métis Settlement lands in Alberta benefited from their forest reserves?
8. Investigate clear-cutting activities on First Nations lands such as the Morley First Nation in southern Alberta during the 90s. Report on your findings by creating a pamphlet.

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SUMMARY Chloroplasts and Photosynthetic Pigments

- Light is a form of energy that travels in the form of photons.
- Chlorophyll *a* is the only pigment that can transfer the energy of light to the carbon fixation reactions of photosynthesis. Chlorophyll *b* and the carotenoids act as accessory pigments, transferring their energy to chlorophyll *a*.
- Chloroplasts have an outer membrane and an inner membrane. The interior space contains a semiliquid material called stroma with a system of membrane-bound sacs called thylakoids, some of which are stacked on top of one another to form grana. Thylakoid membranes contain chlorophyll molecules and electron transport chains.

EXTENSION

Action Spectrum
In this Virtual Biology Lab, you will measure which wavelengths of light are most effective for photosynthesis.

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Section 6.1 Questions

1. (a) How are the wavelength and energy of a photon related?
(b) Which possesses a higher energy value: red light or green light? Explain.
(c) How is the colour of light related to its energy? Provide examples.

2. (a) What pigments are present in green leaves?
(b) Explain why yellow-coloured pigments are visible in autumn leaves but not in summer leaves.

3. What do all photosynthetic organisms have in common?

4. Label parts A, B, C, and D of the chloroplast in **Figure 9**.

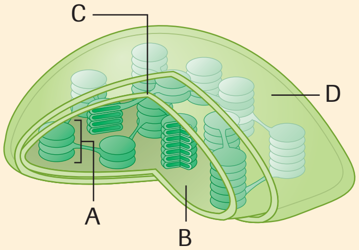

Figure 9
A chloroplast

5. Many lightbulb manufacturers produce fluorescent tubes labelled as “growlights” that they claim emit “full-spectrum light that imitates sunlight.” Conduct research to determine whether fluorescent tubes labelled as “growlights” are more effective sources of artificial light for growing plants indoors than tubes without this label.

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6. Several biotechnology companies are experimenting with the possibility of producing a “green” (environmentally friendly) plastic from plants. One procedure converts sugar from corn to polylactide, a plastic similar to the plastic polyethylene terephthalate, which is used to make pop bottles and a variety of synthetic fabrics. Conduct research to complete the following tasks:
(a) Describe one or two other “green” plastics and their potential uses.
(b) Describe some of the costs and benefits of producing “green” products on a large scale.

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7. Recent advances in remote sensing have made detection of plant health possible on a large scale. Using satellite images, spectral analysis, and other sensing technologies, farmers may now detect problems in large fields of crops before they are identified at ground level. Conduct library and/or Internet research about spectral remote sensing as applied to plants to answer the following questions:
(a) What characteristic(s) of plants do remote sensing systems detect to provide information regarding a crop’s overall health?
(b) Why would a farmer spend money to have crops tested by these methods? What advantages are gained by the procedure?
(c) Describe the strategy or strategies you used to conduct your Internet search. List the advantages and disadvantages of each strategy.

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6.2 The Reactions of Photosynthesis

As you have learned, chlorophyll and other pigments located within the chloroplasts of green plants capture packages of energy called photons from sunlight. During photosynthesis, this captured energy is converted into chemical energy in the bonds of glucose molecules. Each molecule of glucose is synthesized from six molecules of carbon dioxide and six molecules of water.

Photosynthesis is a process made up of a series of complex chemical reactions that form a variety of intermediate and final energy-rich molecules. These molecules serve a number of different energy-related functions within cells (**Table 1**).

+ EXTENSION

A Brief History of Photosynthesis Research

Our current understanding of photosynthesis is constructed from the work of many scientists from the 1600s onward, and the work continues today. Read about some of the classic experiments in photosynthesis research and complete the questions to assess your understanding.

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Table 1 Energy-Containing Molecules Formed during Photosynthesis

Molecule	Function
ATP	• principal energy-supply molecule for cellular functions of all living cells • provides an immediate source of energy for cellular processes, such as growth and movement
NADPH	• electron donor (NADPH) involved in energy transfers
glucose	• transport molecule ("blood sugar") • medium-term energy storage in most cells

Glucose is used to store energy for later use by cells. However, of all the energy-rich molecules in living cells, none is more significant than **ATP** (adenosine triphosphate). ATP is used by all living cells, both plant and animal, to provide immediate energy for cellular functions, such as synthesis of needed chemicals and transport of materials across cell membranes. ATP is formed by the addition of an inorganic phosphate group (P_i) to a molecule of lower-energy **ADP** (adenosine diphosphate). Later, this same energy can be released to the cell by a chemical reaction that splits ATP back into ADP and P_i (**Figure 1**).

ATP a molecule containing three high-energy phosphate bonds that acts as the primary energy-transferring molecule in living organisms

ADP a molecule containing two high-energy phosphate bonds that may be formed by breaking one of the phosphate bonds in ATP

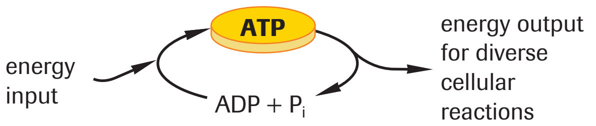

Figure 1
Energy is stored when ATP is formed from a phosphate group and ADP. This energy can be released when needed by the reversal of this reaction.

The compound **NADP$^+$** (nicotinamide dinucleotide phosphate) may also participate in many cellular reactions. At several places during photosynthesis, NADP$^+$ accepts one hydrogen atom and two electrons to form **NADPH**. NADPH may then donate electrons to other molecules in the cell, and so becomes NADP$^+$ again. In the rest of this section, you will find out how the gain and loss of electrons from NADP$^+$ and NADPH contributes to the process of photosynthesis.

NADP$^+$ a compound that accepts one hydrogen atom and two electrons, forming NADPH; is an electron acceptor

NADPH a compound that donates one hydrogen atom and two electrons to another molecule, to reform NADP$^+$; is an electron donor

An Overview of Photosynthesis

As you have learned, chlorophyll molecules and other pigments located within chloroplasts are able to absorb solar energy. To be useful to the plant, this solar energy must be converted to chemical energy. Once the energy is in a chemical form, it can be transported throughout the cell and to other parts of the plant, and it can also be stored.

The pigments and chemicals involved in these pathways are arranged within the chloroplast to make these tasks operate efficiently. While these physical arrangements and chemical pathways are complex and involve many intermediate steps, the overall process is relatively straightforward and can be broken down into the following three distinct, but connected, stages.

Stage 1: *capturing solar energy and transferring it to electrons*

Stage 2: *using captured solar energy to make ATP and to transfer high-energy electrons to* $NADP^+$*; yields NADPH, which is then used as a high-energy electron carrier molecule*

Stage 3: *using energy stored in ATP and high-energy electrons carried by NADPH to form energy-rich organic molecules, such as glucose, from* CO_2

The first two stages involve a series of reactions that are directly energized by light, called the **light-dependent reactions**. These reactions require chlorophyll and occur on the thylakoid membranes in chloroplasts. Chlorophyll absorbs the light energy that is eventually transferred to carbohydrate molecules in the last stage of the process. The reactions of the third stage result in **carbon fixation**—the incorporation of the carbon of CO_2(g) into organic compounds, such as glucose. These reactions take place in the stroma of the chloroplast and utilize the energy of ATP and high energy electrons carried by NADPH. Carbon fixation takes place in the stroma by means of a cyclic sequence of enzyme-catalyzed reactions called the **Calvin cycle** (**Figure 2**). The reactions of the Calvin cycle are **light-independent reactions**.

light-dependent reactions the first set of reactions of photosynthesis in which light energy excites electrons in chlorophyll molecules, powers chemiosmotic ATP synthesis, and results in the reduction of $NADP^+$ to NADPH

carbon fixation the process of incorporating CO_2 into carbohydrate molecules

Calvin cycle a cyclic set of reactions occurring in the stroma of chloroplasts that fixes the carbon of CO_2 into carbohydrate molecules and recycles coenzymes

light-independent reactions the second set of reactions in photosynthesis (the Calvin cycle); these reactions do not require solar energy

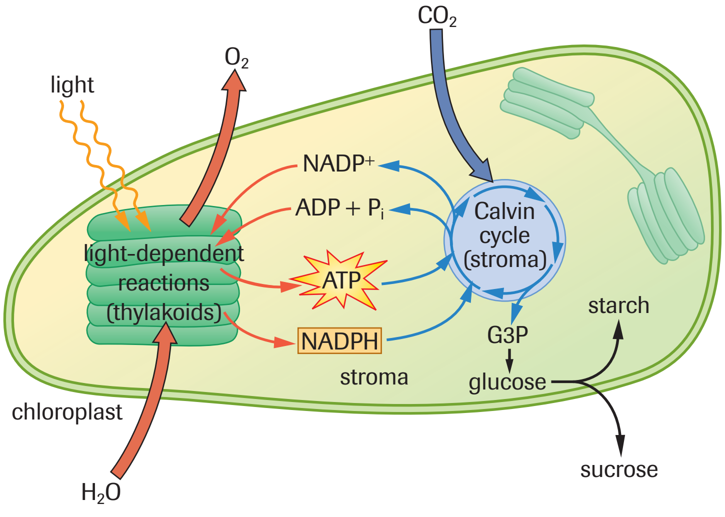

Figure 2
An overview of photosynthesis. The light-dependent reactions of photosynthesis occur in the thylakoid membranes of chloroplasts and transfer the energy of light to ATP and NADPH. The Calvin cycle takes place in the stroma and uses NADPH to reduce CO_2 to organic compounds, such as glucose and other carbohydrates.

Practice

1. Name three energy-containing molecules that are formed during photosynthesis.
2. Where do the light-dependent reactions of photosynthesis take place?
3. Where does carbon fixation take place?

Stage 1: Capturing Solar Energy

photosystem a cluster of photosynthetic pigments embedded in a thylakoid membrane of a chloroplast that absorbs light energy

electron transport chain a series of progressively stronger electron acceptors; each time an electron is transferred, energy is released

photolysis a chemical reaction in which a compound is broken down by light; in photosynthesis, water molecules are split by photolysis

Within the chloroplasts, chlorophyll and other pigment molecules are found in clusters embedded in the thylakoid membranes. These molecule arrangements are called **photosystems**. As you will soon see, the light-dependent reactions rely on two distinct but interconnected photosystems—photosystems I and II—numbered in order of their discovery. These molecules are responsible for the actual capturing of light energy.

Solar energy is captured when an electron in a chlorophyll molecule (or in another pigment molecule) absorbs a photon. Electrons are high-energy particles present in all atoms. Before a photon of light strikes, the electron has a relatively low amount of energy. After the photon is absorbed, the electron has a relatively high amount of energy, and is said to be excited. The photon has now been converted to chemical energy!

Still in the thylakoid membrane, the excited electron is then removed from the photosystem and passed from one molecular complex to another in a long series of steps often referred to as an **electron transport chain**.

The electrons that are being removed from each photosystem to enter the electron transport chain must be replaced. These replacement electrons come from water molecules, in a process call photolysis. In **photolysis**, the solar energy absorbed by the chlorophyll is used to split water into hydrogen ions (H^+) and oxygen gas. Photolysis occurs in the thylakoid lumen.

Two water molecules are consumed for every four electrons transferred to a photosystem.

$$2\ H_2O(l) + \text{energy} \rightarrow 4\ H^+ + 4\ e^- + O_2(g)$$

EXTENSION

Is Light Necessary for Photosynthesis?
Plants seem to need light to stay alive. In this activity, you will analyze leaves exposed to sunlight and leaves "starved" of sunlight to determine whether leaves need light to produce starch, a molecule made from glucose.

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Practice

4. Where are photosystems I and II located?
5. What happens when chlorophyll absorbs a photon?
6. How are the electrons that are passed on to the electron transport chain replaced?

Stage 2: Electron Transfer and ATP Synthesis

The solar energy captured by the pigments within photosystems must now be used to form additional stable energy-rich molecules and to make ATP from ADP and P_i. These tasks are performed by two distinctly different mechanisms—one involving the buildup of charged particles and the other involving the direct transfer of electrons.

The Electron Transport Chain

Both of these mechanisms depend on the electron transport chain. In many ways, the electron transport chain is similar to the set of stairs shown in **Figure 3** on the next page. Solar energy is used to excite electrons that have been removed from a water molecule. This added energy lifts them up in a single leap to the top of the energy stairway (the electron transport chain). This potential energy is then gradually released as the electrons travel down the stairs to their original lower energy level. Some of this released energy is captured to make ATP. The electrons eventually rejoin H^+ ions in the formation of new compounds.

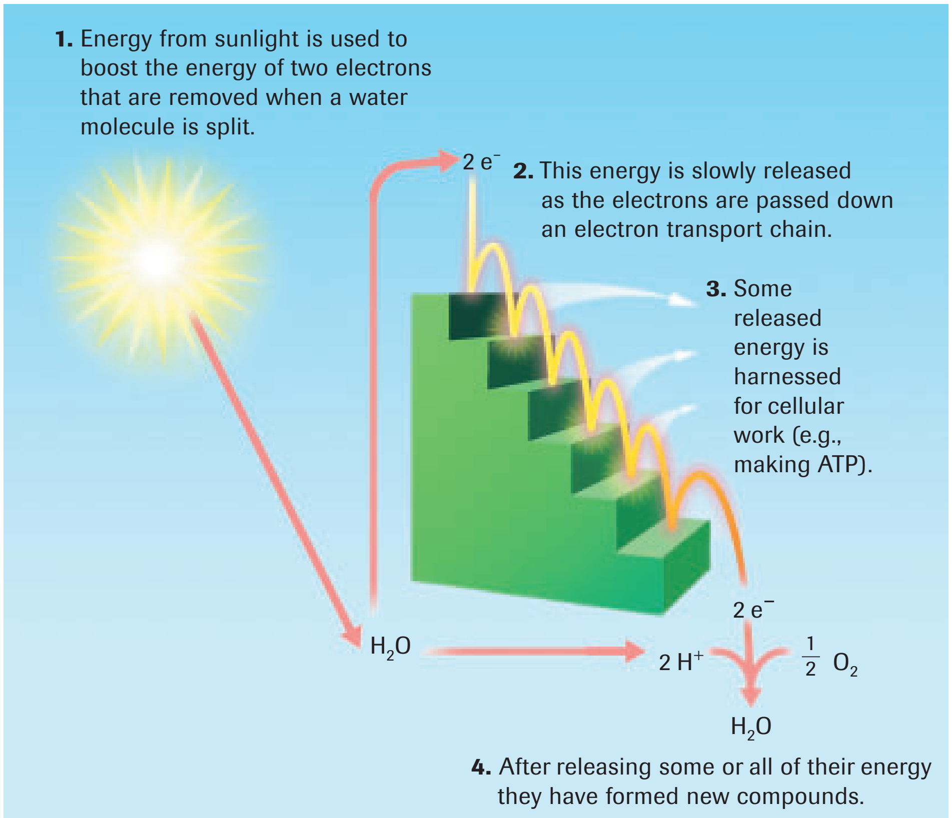

Figure 3
The step-by-step release of energy by electron transport chains enables cells to release energy in smaller, usable amounts.

CHEMISTRY CONNECTION

Energy
There are two classes of energy: potential energy and kinetic energy. In simple terms, potential energy is stored energy and kinetic energy is the energy of motion. The energy captured in photosynthesis is potential energy. Your chemistry textbook contains more information on the types of energy.

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Oxidation–Reduction Reactions

How does the transfer of electrons release energy? At each step in the electron transport chain, a higher-energy electron donor passes an electron to a lower-energy electron acceptor. Such reactions are called oxidation–reduction or redox reactions. An **oxidation** is a reaction in which an atom or molecule loses electrons. A **reduction** is a reaction in which an atom or molecule gains electrons. An electron transfer between two substances always involves both an oxidation and a reduction.

Electron donors, such as NADPH (an electron carrier in the electron transport chain in chloroplasts), tend to lose electrons. Electron acceptors, such as $NADP^+$, tend to gain electrons. When NADPH is oxidized, it loses a hydrogen nucleus (H^+) and its two electrons (2 e^-), and is converted to $NADP^+$. When $NADP^+$ is reduced, it gains a hydrogen nucleus and its two electrons, and is converted to NADPH. When an element or molecule gains electrons (is reduced), it releases energy and becomes more stable. Therefore, whenever $NADP^+$ is converted to NADPH, energy is released. NADPH then donates electrons to other molecules for other processes in the cell, such as in the dark reactions of photosynthesis (Stage 3).

oxidation a reaction in which an atom or molecule loses electrons

reduction a reaction in which an atom or molecule gains electrons

Learning *Tip*

Remember: LEO goes GER.
Loss of Electrons is Oxidation;
Gain of Electrons is Reduction

Practice

7. What happens to the electrons that are released during photolysis?
8. What is the role of electron donors and electron acceptors in the steps of the electron transport chain?
9. What is an oxidation? What is a reduction?
10. What is the role of oxidations and reductions in the electron transport chain?

EXTENSION

Electron Transport in the Thylakoid Membrane

Listen to this Audio Clip for information on how changes in the energy levels of electrons allow plants to capture and transform light energy into chemical energy through the process of photosynthesis.

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Let's now follow the pathway of other electrons that were first excited by light in photosystem II (**Figure 4**). As the electrons are passed along an electron transport chain from one chemical complex to another, they are also carried across the thylakoid membrane—from the outer surface—toward the thylakoid lumen, as seen in (**A**). In doing so, they release energy, which is used to "pull" a number of positively charged hydrogen ions

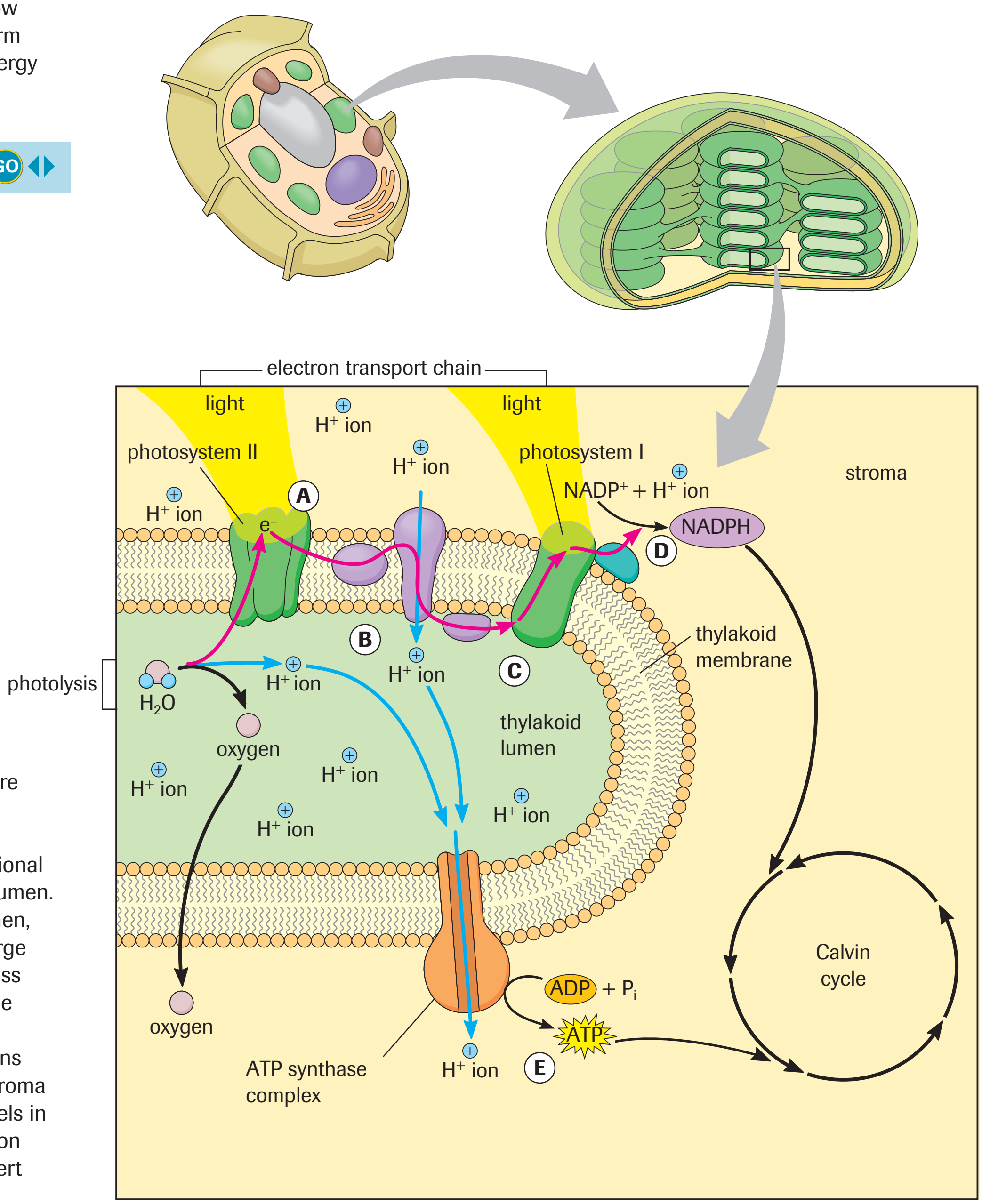

Figure 4
H^+ ions are released into the thylakoid lumen as electrons are removed from water. As these electrons are passed along an electron transport chain, additional H^+ ions are pumped into the lumen. H^+ ions accumulate in the lumen, increasing the gradient of charge and H^+ ion concentration across the thylakoid membrane. As the concentration and electrical gradients begin to build, H^+ ions move from the lumen to the stroma through special protein channels in the thylakoid membrane. The ion flow drives enzymes that convert ADP and P_i into ATP.

(H^+) across the membrane into the lumen (**B**). The electrons have now lost much of the energy that they received from light in photosystem II. However, their journey is not over. As H^+ ions are continuously pulled across the thylakoid membrane, their concentration increases inside the lumen and a positive charge begins to build up.

After moving to the inside of the thylakoid membrane, the electrons are transferred to a second photosystem—photosystem I (**C**). Here, they replace electrons that are energized by light. The electrons that are energized in photosystem I, unlike those in photosystem II, are not passed across the thylakoid membrane. Instead, they are transferred via a series of chemical complexes to $NADP^+$ (**D**). Each $NADP^+$ is able to accept two high-energy electrons and an H^+ ion from the surroundings as it changes to NADPH. The NADPH molecules formed in this process are used to transfer high-energy electrons to the Calvin cycle in Stage 3.

Key steps in electron transfer during the light-dependent reactions of photosynthesis are:

1. Electrons from photosystem II are transferred along an electron transport chain and across the thylakoid membrane to the inner surface.
2. Some of their energy is used to pull H^+ ions across the membrane, resulting in a buildup of positive charge within the lumen.
3. The electrons, having lost much of their original energy, are then transferred to chlorophyll molecules in the photosystem I complex, where they again absorb solar energy and reach an excited state.
4. High-energy electrons from photosystem I are transferred to $NADP^+$ to form NADPH.

DID YOU KNOW?

The Cost of Chlorophyll

Leaves from shade-tolerant plants have more chlorophyll per photosystem than leaves from light-loving plants. This added cost is necessary to ensure enough light is captured for photosynthesis.

Chemiosmosis

Recall the H^+ ions that were pulled across the thylakoid membrane by the first electron transport chain at position (**B**). This process results in increasing concentration and electrical gradients across the thylakoid membrane. These gradients can now be put to good use. The H^+ ions are unable to escape from the lumen except through specialized protein complexes embedded in the membrane, named **ATP synthase complexes**. As the H^+ ions rush through these complexes, they release energy. The complexes are able to use some of the energy released by H^+ ions to combine ADP with P_i. The process of making ATP using the energy from an H^+ ion gradient is called **chemiosmosis**. Note that the energy stored in the H^+ ion gradient is derived from the energy of the electrons energized by photosystem II. As a result, it can be stated that the energy used by the plant to make ATP originally comes from sunlight.

Overall, the light-dependent reactions consume water and result in the formation of ATP, NADPH, and oxygen. ATP and NADPH play a critical role in the next phase of photosynthesis: carbon fixation.

ATP synthase complex a specialized protein complex embedded in the thylakoid membrane that allows H^+ ions to escape from the lumen and uses the resulting energy to generate ATP

chemiosmosis a process for synthesizing ATP using the energy of an electrochemical gradient and the ATP synthase enzyme

Practice

11. Where does the energy used to pull H^+ into the thylakoid lumen come from?
12. What are the H^+ ions that are pulled inside the thylakoid membranes used for?
13. Why is the production of NADPH important?
14. What is chemiosmosis?

Figure 5
Dr. Rudolph Arthur Marcus

WWW **WEB Activity**

Canadian Achiever—Dr. Rudolph Arthur Marcus

The formation of ATP during photosynthesis depends on the transfer of electrons. Dr. Marcus (**Figure 5**), born and educated in Montreal, Quebec, was a main contributor to the development of this idea. From 1956 to 1964, he published a number of papers on what is now called the Marcus theory of electron transfer reactions. The Marcus theory also explained other phenomena that are very different from photosynthesis. Find out more about the life and work of Marcus, and then explain how his work contributed to our understanding of photosynthesis.

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EXPLORE an issue

Harnessing Light Energy

Issue Checklist

- ● Issue
- ○ Design
- ● Analysis
- ● Resolution
- ● Evidence
- ● Evaluation

By utilizing sunlight, plants produce food through photosynthesis. When we use plants for food, we are using photosynthesis to meet our basic biological energy demands. Photosynthesis also supplies the wood we use as fuel, and was even responsible for producing the fossil fuels we use today. However, with an ever-increasing demand for abundant, environmentally friendly energy supplies, scientists are researching and refining artificial technologies for capturing and utilizing light energy.

Photosynthesis converts light energy directly into chemical energy. However, the most widely used solar technologies to date convert solar energy into heat (solar collectors such as rooftop solar hot-water heaters) or electrical energy (solar (photovoltaic) cells).

Recently, scientists have started to investigate mimicking photosynthesis by using chemical processes to create artificial photosynthetic systems. Some researchers believe that such artificial photosynthetic technology holds great promise. Some scientists are researching how to directly harness solar energy in the form of ATP, while others are attempting to mimic the carbon fixation reactions in the Calvin cycle. One research team is designing and using artificial catalysts that are able to use solar energy to convert CO_2 to CO—the first stage in the fixation of carbon. This could lead to the production of inexpensive fuels such as methanol and raw materials for the chemical industry.

How do these three technological approaches: converting solar energy into heat energy, electrical energy, and chemical energy compare to the efficiency of plant photosynthesis? What are the advantages and disadvantages of each method as a source of clean energy?

1. Conduct library and/or Internet research to investigate current efforts in the field of solar energy technologies.

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   (a) How efficient are plants at converting solar energy into useable biomass energy?
   (b) How efficient are solar collectors? What are the advantages and disadvantages of such systems?
   (c) How efficient are photovoltaic cells? What are the advantages and disadvantages of such systems?
   (d) Why is it important to factor in life expectancy and cost when judging the value of a new technological innovation?
   (e) Has artificial photosynthesis been achieved?
   (f) What are the possible applications of artificial photosynthetic systems? Outline the advantages they might have over non-photosynthesis-based methods.

2. As a scientific researcher, you are attending an upcoming environmental conference to discuss artificial photosynthesis. Prepare a brochure or slide presentation highlighting the possible applications of this new technology.

Stage 3: The Calvin Cycle and Carbon Fixation

The final stage of photosynthesis is carbon fixation, which is the formation of high-energy organic molecules from CO_2. This process is referred to as the Calvin cycle, in honour of Melvin Calvin, who won the 1961 Nobel Prize in Chemistry for his work in discovering this pathway. The cycle involves a large number of light-independent reactions and is presented in a simplified form in **Figure 6** on the next page.

The Calvin cycle utilizes both ATP molecules and high-energy electrons carried by NADPH from the light-dependent reactions (Stages 1 and 2) to make G3P, a sugar that is

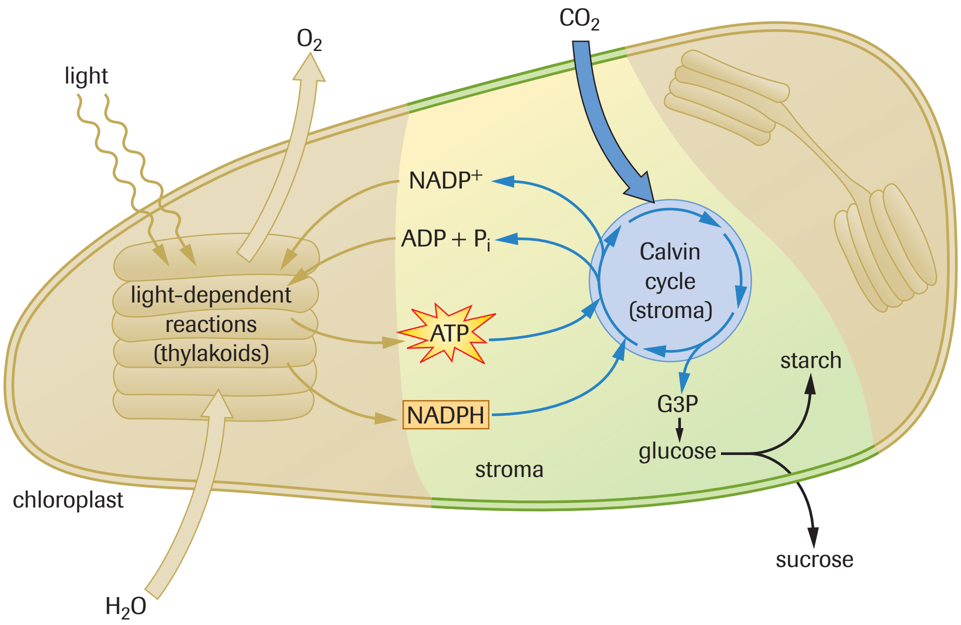

Figure 6
The Calvin cycle is the final stage of photosynthesis and takes place in the stroma. It uses NADPH and ATP to reduce CO_2 to G3P, a sugar that is used to make glucose and other carbohydrates, such as sucrose, cellulose, and starch.

used to create glucose. In these carbohydrates, the carbon and oxygen atoms are supplied by the CO_2 while the hydrogen atoms are supplied by the light-dependent reactions. Three ATPs and two NADPHs are consumed for every CO_2 that enters the cycle. Therefore, the building of even one simple sugar molecule such as glucose ($C_6H_{12}O_6$) requires the energy from 18 ATP molecules and the electrons and protons carried by 12 NADPH molecules.

Note that the amount of water produced during the Calvin cycle is less than that consumed during the light-dependent reactions. In total, there is a net consumption of six water molecules for every one glucose molecule formed.

In order for the Calvin cycle to operate within the stroma of the chloroplast, CO_2 must be readily available. In most plants CO_2 diffuses directly into the photosynthesizing plant leaf cells and chloroplasts from air spaces within the leaves. These air spaces are connected to the outside environment via tiny openings in the surface of the leaves.

DID YOU KNOW?

Benson and Bassham

Melvin Calvin did not explain carbon fixation on his own. Andrew Benson and James Bassham also made significant contributions. The Calvin cycle is therefore also called the Calvin-Benson cycle or the Calvin-Benson-Bassham (CBB) cycle.

Practice

15. Where in the chloroplast does the Calvin cycle occur?

16. Name the final product of the Calvin cycle. What happens to this compound?

INVESTIGATION 6.2 *Introduction*

How Does Carbon Dioxide Concentration Affect the Rate of Photosynthesis?

Photosynthesis involves light-dependent reactions and biochemical reactions that do not directly require solar energy. Plants live in a variety of environments on Earth. Do changes in environmental conditions affect the rate of photosynthesis? In Investigation 6.2. you will design experiments to measure the rate of photosynthesis in various conditions of light intensity, temperature, CO_2 concentration, and other factors.

Report Checklist

- ○ Purpose
- ○ Problem
- ○ Hypothesis
- ● Prediction
- ● Design
- ○ Materials
- ● Procedure
- ● Evidence
- ● Analysis
- ● Evaluation
- ● Synthesis

To perform this investigation, turn to page 197.

WEB Activity

Web Quest—Factors Affecting Photosynthesis

How do different variables affect photosynthesis? Is it possible to speed it up or slow it down, just by changing the colour or intensity of light? How does the CO_2 present affect photosynthesis? This Web Quest lets you design experiments in a computer simulation to find the answers to these questions and more. See if you can figure out the optimal levels of different variables for the optimal rate of photosynthesis!

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SUMMARY The Reactions of Photosynthesis

- The light-dependent reactions of photosynthesis take place within chloroplasts in two stages:
  - Stage 1: Both photosystems I and II capture light energy and transfer it to electrons.
  - Stage 2: The energy transferred to the electrons is used to produce a buildup of H^+ ions inside the thylakoid space, and to produce high-energy NADPH molecules.
- The light-dependent reactions consume water and form ATP, NADPH, and oxygen.
- The following events occur in chemiosmosis during Stage 2:
  - H^+ ions are pulled across the thylakoid membrane by the electron transport chain, creating an H^+ ion gradient and a buildup of positive charge within the lumen.
  - The H^+ ions leave the lumen, passing through ATP synthase complexes embedded in the thylakoid membrane.
  - The concentrated H^+ ions release energy as they escape from the thylakoid space and this energy is used to form high-energy ATP molecules.
- The Calvin cycle is Stage 3 of photosynthesis and takes place in the stroma. It uses NADPH and ATP to reduce CO_2 to G3P, which is then used to make glucose. Glucose is then made into other carbohydrates.
- Building one simple sugar molecule such as glucose ($C_6H_{12}O_6$) requires the energy from 18 ATP molecules and the electrons and protons carried by 12 NADPH molecules.

Section 6.2 Questions

1. What is ATP?

2. Write an equation to represent the overall reaction of photosynthesis.

3. (a) What is the primary function of photosynthesis?
(b) Where in the chloroplast do the light-dependent reactions occur?
(c) What are the products of the light-dependent reactions?
(d) In what phase of photosynthesis are the products of the light-dependent reactions used?

4. (a) Name the gas released as a byproduct of the light-dependent reactions of photosynthesis.
(b) Name the molecule that is the source of this gas.

5. In an experiment, a bean plant is illuminated with green light and another bean plant of similar size is illuminated with equally intense blue light. If all other conditions are controlled, how will the photosynthetic rates of the two plants most probably compare?

6. (a) How many molecules of CO_2 must enter the Calvin cycle for a plant to ultimately produce a sugar, such as sucrose, that contains 12 carbon atoms?
(b) How many ATP molecules will be used?
(c) How many NADPH molecules will be used?

7. On a sheet of blank paper, draw a labelled diagram with a single caption to teach the process of photosynthesis to a grade 4 student who has never heard of the process.

INVESTIGATION 6.1

Separating Plant Pigments from Leaves

Report Checklist

- ● Purpose
- ● Problem
- ○ Hypothesis
- ● Prediction
- ○ Design
- ○ Materials
- ○ Procedure
- ● Evidence
- ● Analysis
- ● Evaluation
- ○ Synthesis

Plants produce thousands of different chemical compounds, many of which have been found to be useful in medicine, as foods, and in industry. The first step to finding useful plant compounds is to separate the components of a plant tissue. The properties of each separate component may then be tested and the compound identified. Chromatography is a technique that separates different chemicals in a mixture based on their solubility in a particular solvent solution. In this activity, you will use paper chromatography to separate some of the different pigments found in a plant leaf.

Materials

safety goggles	test-tube rack
laboratory apron	scissors
spinach leaf	pencil
chromatography solvent (acetone)	chromatography tube with cork stopper
filter paper, 12 cm long	cork stopper with a paper-clip hook
dime	

The chromatography solvent is volatile and flammable.

Use the solvent only under a fume hood.

Do not use the solvent in a room with an open flame.

Chemicals should be dispensed only by the teacher.

Wear eye protection and a laboratory apron at all times.

Procedure

1. Obtain a piece of filter paper that is long enough so the tip of the strip reaches the solvent when the strip is suspended in the test tube. Handle the paper by the edges only, to avoid transferring oil from your skin.
2. With the scissors, trim the filter paper to a point at one end. At 3 cm above the point, draw a light line in pencil across the width of the filter paper.
3. Obtain a fresh spinach leaf and place it over the pencil line on the filter paper.
4. Roll the edge of a dime across the leaf, so that the dime edge crushes the leaf tissue onto the filter paper along the pencil line.
5. Repeat step 4 several times until the pencil line has been soaked with a thin, dark band of spinach leaf extract.
6. Obtain the cork stopper with a hook formed from a paper clip. Insert the hook into the upper (straight) edge of the chromatography paper strip.
7. Obtain a chromatography tube containing 3 mL of chromatography solvent from your teacher. Keep the tube tightly stoppered and standing upright in the test tube rack.
8. Under the fume hood, remove the cork stopper that is in the chromatography tube. Replace it with the stopper to which you attached the paper strip in step 6, as shown in **Figure 1**. The tip of the paper must just touch the solvent, and the line of leaf extract must stay above the surface of the solvent. Ensure that the chromatography paper is not touching the sides of the chromatography tube. Tightly stopper the chromatography tube and carefully stand the tube upright in the test tube rack.

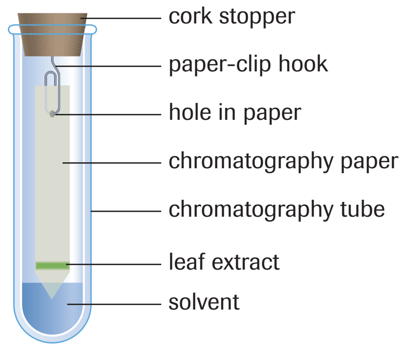

Figure 1
A chromatography setup

9. Observe the movement of solvent and extract for 15 min to 30 min. Remove the paper strip before the solvent reaches the top of the paper, and replace the stopper in the tube.
10. Still working under the fume hood, draw a pencil line across the paper strip at the uppermost point reached by the solvent before it dries and becomes invisible. Also mark each pigment band and record its colour before it fades. Keep the paper strip under the fume hood until it is completely dry.

INVESTIGATION 6.1 *continued*

(a) At your desk, measure and record the distance from the original pencil line to the middle of each pigment band. Also measure and record the distance the solvent travelled from the pencil line.

Analysis

(b) After chromatography, compounds may be identified from their R_f values. These values compare the distance travelled by a compound with the distance travelled by the solvent. Calculate the R_f values for each compound on your filter paper according to the following equation:

$$R_f = \frac{\text{distance travelled by compound}}{\text{distance travelled by solvent}}$$

(c) How many compounds were you able to separate using chromatography?

(d) Draw a life-sized diagram of your chromatography strip, showing the precise locations of the pigments and solvent solution.

Evaluation

(e) The more soluble a compound is in a solvent, the farther it will travel during chromatography. **Table 1** gives some properties of pigments commonly found in plant leaves. Which pigments were in your leaf extract? Explain your answer.

Table 1 Common Leaf Pigments

Pigment	Colour	Relative solubility in acetone
chlorophyll *a*	bright green to blue-green	medium
chlorophyll *b*	yellow-green to olive green	medium–low
carotenes	dull yellow-orange	high
xanthophylls	bright yellow to orange	medium–high

(f) List the R_f values for the pigments you identified in the preceding question. Describe the relationship between R_f value and solubility.

(g) Compare your R_f values to those recorded by the other groups in your class. Were the R_f values for each pigment always the same? How might this affect the use of R_f values to identify chemical compounds?

(h) Suggest a step that could be added to the procedure to isolate a specific compound for chemical testing.

Extension

(i) Obtain a black water-soluble marker. Repeat steps 1 to 3, but replace the solvent with water and use the marker to draw a line across a piece of filter paper in step 3. Allow the ink to dry and then draw another line on top of the first. Repeat this several times until you have a very dark ink line across the paper. Perform a chromatography as in this activity. Report your findings to the class.

(j) The colourful Haida mask in **Figure 2** may have been dyed using pigments obtained from local plants. Brainstorm methods the Haida people might use to extract these pigments from leaves, roots, and stems.

Figure 2
Haida mask

EXTENSION

Chromatography
In this Virtual Biology Lab, you can use TLC (thin-layer chromatography) to separate and analyze the pigments in a spinach leaf extract.

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INVESTIGATION 6.2

How Does Carbon Dioxide Concentration Affect the Rate of Photosynthesis?

Report Checklist

○ Purpose	● Design	● Analysis
○ Problem	○ Materials	● Evaluation
○ Hypothesis	● Procedure	● Synthesis
● Prediction	● Evidence	

Photosynthesis involves light-dependent reactions and biochemical reactions that do not directly require light. Plants live in a variety of environments on Earth. Do changes in environmental conditions affect the rate of photosynthesis? In this investigation, you will measure the rate of photosynthesis in various conditions by quantifying the amount of oxygen being released from a photosynthesizing solution.

Problems

1. How do changes in light intensity, temperature, and CO_2 concentration affect the rate of photosynthesis?
2. Develop your own question regarding the effect of an environmental condition of your choice on the rate of photosynthesis.

Predictions

(a) Predict the effect that changes in each of the following environmental conditions will have on the rate of photosynthesis:
  (i) light intensity
  (ii) temperature
  (iii) CO_2 concentration
  (iv) another environmental condition of your choice

Design

The procedure outlined in this investigation provides a method for measuring the rate of photosynthesis of plants submersed in an aqueous sodium bicarbonate buffer (pH 7). Sodium bicarbonate is used as a source of CO_2(aq). You will use this procedure to measure the rate of photosynthesis in four experiments that you will design and perform. In each case, you must conduct controlled experiments that allow you to make reasonable comparisons.

(b) Design three experimental procedures to determine
  (i) the effect of varying light intensity on the rate of photosynthesis
  (ii) the effect of varying temperature on the rate of photosynthesis
  (iii) the effect of varying concentration of dissolved carbon dioxide on the rate of photosynthesis

Have your teacher approve each experimental procedure, then carry out the experiments. Use the procedure outlined in this investigation to measure the rate of photosynthesis in each case. Record all observations and measurements in a suitable table format.

(c) Design an experimental procedure to test the prediction you made in (a) (iv). Obtain teacher approval, then carry out the experiment. Record all observations and measurements in suitable table format.

Materials

safety goggles
laboratory apron
500 mL conical flask or large test tube
plants (terrestrial plants or water plants)
sodium bicarbonate buffer, pH 7
rubber stopper with glass tubing
rubber tubing
50 mL burette
distilled water
500 mL beaker
utility stand and clamp
rubber bulb
ice
sodium bicarbonate
thermometer
light intensity meter
other materials and equipment as necessary
200 W light bulb

Procedure

1. Put on your safety goggles and lab apron.
2. Fill the 500 mL conical flask with plant material.
3. Add enough sodium bicarbonate buffer to submerse the plant material.
4. Put the stopper with glass tubing onto the mouth of the conical flask. Make sure that the glass tubing does not touch the contents of the flask.
5. Place 400 mL of water into a 500 mL beaker. Fill the burette with water to the top, then invert it in the beaker and secure it with a clamp to the utility stand (**Figure 1**, next page).
6. Use rubber tubing to connect the open end of the glass top in the stopper of the flask to the bottom of the burette. The rubber tubing needs to be air tight within the glass tubing, but should fit loosely in the bottom of the burette. Be sure there is space for the water to escape when the gas bubbles up the burette.

INVESTIGATION 6.2 *continued*

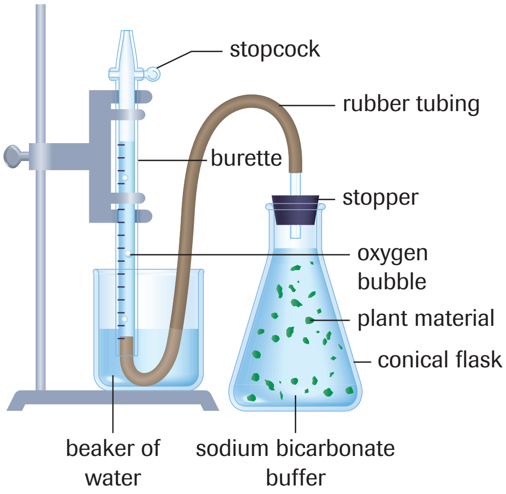

Figure 1
Gas collection apparatus setup

7. Open the burette stopcock carefully and allow the water level to drop to the 50 mL level on the burette.
8. Subject the system to conditions according to your design. Allow several minutes for the system to stabilize.
9. Follow the rate of photosynthesis by either counting the number of bubbles over 1 min spans or measuring the amount of water displaced over 5 min spans. Measure for a total of 10 min for each condition. If you get no bubbles, check if the meniscus in the tubing is moving. If it is, then your burette valve is leaking. Your teacher will help you correct this problem.

Analysis

(d) In tables, summarize the results for the variables you tested. Draw suitable graphs using your data.

(e) Analyze your results for trends and patterns. Answer the Questions.

(f) Compare your results with those of the rest of the class.

Evaluation

(g) In your report, evaluate your predictions, taking into account possible sources of error. Draw reasonable conclusions.

(h) Describe how you could improve your experimental methods and the assay technique.

(i) Suggest other experiments you could perform to extend your knowledge of photosynthetic activity.

(j) The experiments you conducted in this investigation were carried out with plants submerged in water. Design a procedure for carrying out the same types of experiments in air instead of water. Draw a labelled diagram, like **Figure 1**, to illustrate your experimental design.

(k) What environmental conditions affecting the rate of photosynthesis can be tested in an air environment that could not be tested in a water environment?

Synthesis

(l) Suggest a procedure you might use to identify the type of gas produced by the plant material in these experiments.

EXTENSION

Carbon Dioxide Fixation

You can confirm the results of the experiment you designed or carry out additional experiments on factors that affect the rate of photosynthesis in the Virtual Biology Lab.

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Chapter 6 SUMMARY

Outcomes

Knowledge

- explain, in general terms, how pigments absorb light and transfer that energy as reducing power in $NADP^+$, NADPH, and finally into chemical potential in ATP by chemiosmosis, describing where those processes occur in the chloroplast (6.1, 6.2)
- explain, in general terms, how the products of the light-dependent reactions, NADPH and ATP, are used to reduce carbon in the light-independent reactions for the production of glucose, describing where the process occurs in the chloroplast (6.2)

STS

- explain how scientific knowledge may lead to the development of new technologies and new technologies may lead to scientific discovery (6.2)
- explain that the appropriateness, risks, and benefits of technologies need to be assessed for each potential application from a variety of perspectives, including sustainability (6.2)

Skills

- ask questions and plan investigations (6.1, 6.2)
- conduct investigations and gather and record data and information (6.1, 6.2)
- analyze data and apply mathematical and conceptual models by: collecting and interpreting data and calculating R_f (reference flow) values from chromatography experiments (6.1); and drawing analogies between the storage of energy by photosynthesis and the storage of energy by active solar generating systems (6.2)
- work as members of a team and apply the skills and conventions of science (all)

Key Terms

6.1

photon
chlorophyll
chloroplast
stroma
thylakoid
grana
lamellae
thylakoid membrane
thylakoid lumen

6.2

ATP
ADP
$NADP^+$
NADPH
light-dependent reactions
carbon fixation
Calvin cycle
light-independent reactions
photosystem
electron transport chain
photolysis
oxidation
reduction
ATP synthase complex
chemiosmosis

MAKE a summary

1. Using a large piece of paper, draw a poster summarizing the three stages of photosynthesis. The paper represents the cytoplasm of a plant cell. Draw a chloroplast covering at least half ot the paper. Place different drawings representing each stage of the process in the appropriate locations.
2. Revisit your answers to the Starting Points questions at the start of the chapter. Would you answer the questions differently now? Why?

Go To

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The following components are available on the Nelson Web site. Follow the links for *Nelson Biology Alberta 20–30*.

- an interactive Self Quiz for Chapter 6
- additional Diploma Exam-style Review Questions
- Illustrated Glossary
- additional IB-related material

There is more information on the Web site wherever you see the Go icon in the chapter.

EXTENSION

CBC radio ONE QUIRKS & QUARKS

Low Light Life

Dr. Tom Beatty, (a microbiologist from the University of British Columbia) and his team have discovered photosynthetic bacteria in the deep-sea oases formed around hydrothermal vents. This bacteria uses the light generated by infrared energy from the hot environment and stray photons produced by chemical reactions.

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Many of these questions are in the style of the Diploma Exam. You will find guidance for writing Diploma Exams in Appendix A5. Science Directing Words used in Diploma Exams are in bold type. Exam study tips and test-taking suggestions are on the Nelson Web site.

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DO NOT WRITE IN THIS TEXTBOOK.

Part 1

1. The raw materials for photosynthesis are
   A. oxygen and water
   B. carbon dioxide and water
   C. glucose and oxygen
   D. oxygen and carbon dioxide

2. The word equation that summarizes photosynthesis is
   A. water + starch → glucose + glucose + glucose
   B. water + carbon dioxide → oxygen + glucose
   C. glucose + oxygen → water + carbon dioxide
   D. carbon dioxide + glucose → water + oxygen

Use the following information to answer questions 3 and 4.

Figure 1 shows events taking place inside the chloroplast during photosynthesis. The tan region is the stoma and the green region is the thylakoid lumen. These regions are separated by the thylakoid membrane.

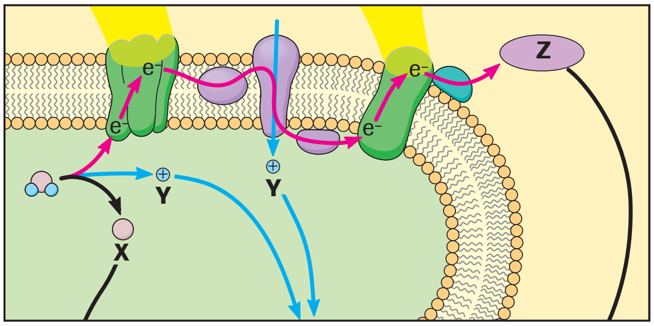

Figure 1

3. The letters X, Y, and Z represent
   A. water (X), NADPH (Y), H^+ (Z)
   B. chlorophyll (X), oxygen (Y), ATP (Z)
   C. NADPH (X), H^+ (Y), water (Z)
   D. oxygen (X), H^+ (Y), NADPH (Z)

4. The function of the electron transport chain in this pathway is to
   A. energize electrons for the reduction of $NADP^+$
   B. pump H^+ ions out of the lumen to generate ATP
   C. move electrons from photosystem I to photosystem II
   D. produce oxygen

5. The process of splitting water to release hydrogen ions, electrons, and oxygen occurs
   A. during the light-dependent reactions
   B. during the Calvin cycle
   C. during photorespiration
   D. during carbon fixation

6. The process of incorporating the carbon of carbon dioxide into carbohydrates occurs
   A. during the light-dependent reactions
   B. during the Calvin cycle
   C. during carbon fixation
   D. during B and C

Use the following information to answer questions 7 and 8.

The herbicide 3-(3,4-dichlorophenyl)-1,1 -dimethylurea (DSMU) blocks the transfer of electrons from photosystem II into the electron transport chain.

7. This herbicide would effect ATP and glucose production in the following ways:
   A. increase ATP production; decrease glucose production
   B. decrease ATP production; increase glucose production
   C. stop ATP production; stop glucose production
   D. decrease ATP production; stop glucose production

8. The herbicide will kill the plant because it will
   A. stop the production of glucose and other carbohydrates
   B. stop the production of ATP
   C. stop the production of oxygen gas
   D. stop the pumping of H^+ ions across the thylakoid membrane

9. NR The following data were collected from several different chromatography experiments using the same solvent. Calculate the R_f values for each of the pigments and then place these values in order from most soluble to least soluble. (Record all four digits of your answer, rounded to two decimal places.)

Pigment	A	B	C	D
Solvent distance travelled	12.1 mm	6.0 mm	8.4 mm	9.5 mm
Pigment distance travelled	5.8 mm	2.2 mm	8.1 mm	1.4 mm

10. NR Place the following molecules in the order that they first appear directly in the chemical pathways of photosynthesis. (Record all four digits of your answer.)
    1. CO_2
    2. glucose
    3. oxygen
    4. water

Part 2

11. (a) **Determine** which has more energy: short wavelengths or long wavelengths of electromagnetic radiation.
(b) **Identify** the range of wavelengths plants use in photosynthesis.

12. Some old biology textbooks called the carbon fixation reactions of photosynthesis the "dark reactions."
(a) **Why** did they use this term?
(b) **Why** is this misleading?

Use the following information to answer questions 13 to 18.

The data in **Table 1** were obtained by extracting the pigments from spinach leaves and placing them in an instrument called a spectrophotometer that measures the amount of light (of different wavelengths) absorbed by pigments.

Table 1 Absorption Spectrum of Spinach Leaf Pigments

Wavelength (nm)	Absorbance (%)	Wavelength (nm)	Absorbance (%)
400	0.42	560	0.12
420	0.68	580	0.15
440	0.60	600	0.17
460	0.58	620	0.25
480	0.83	640	0.40
500	0.23	660	0.32
520	0.11	670	0.56
540	0.12	680	0.24

13. DE **Sketch** a line graph of the data with percent absorbance along the vertical axis and wavelength along the horizontal axis. Indicate the colours of the visible spectrum corresponding to the wavelengths along the horizontal axis.

14. DE **Identify** the colours of an intact spinach leaf that would be least visible. Explain.

15. DE **Identify** the colour that is least absorbed by the pigment extract. Explain.

16. DE **Compare** this graph to the absorption spectrum in **Figure 3** on page 182. Identify the pigment most likely responsible for the peak at 670 nm.

17. DE **Why** are there no peaks in the range of 500 nm to 620 nm?

18. DE **Identify** the pigments primarily responsible for absorption in the range of 400 nm to 480 nm.

Use the following information to answer questions 19 to 21.

A research scientist is able to remove and isolate chloroplasts from plant cells. She places them in an acidic solution of pH 4 (having a very high H^+ concentration) and waits until both the stroma and inner thylakoid space reach this same pH level. She then removes the chloroplasts and places them in a solution of pH 8 in the dark. She notices that the chloroplasts begin synthesizing ATP.

19. DE **Explain** the scientist's observations.

20. DE **Why** did she choose to perform the experiment in the dark rather than the light?

21. DE **Describe** the expected result if she had tested for the presence of products from the Calvin cycle? Explain.

Use the following information to answer questions 22 to 24.

Supplies of fossil fuels are limited, and concerns over increasing atmospheric CO_2 levels are providing an incentive to make better use of solar energy. In the future, photosynthetic organisms may be used to harness solar energy to produce clean-burning fuels, such as ethanol or hydrogen gas. Researchers have already had some success getting certain algae to produce hydrogen gas from water using photosystem II, while others are attempting to harness photosynthesis processes to produce methane gas (CH_4).

22. DE **Describe** the advantages of hydrogen gas as a fuel compared to methane.

23. DE Considering all of the products of photosynthesis, **describe** a safety problem that might arise if either of these fuels were being produced in large quantities by photosynthetic processes.

24. DE If photosynthesis were used as a source of methane gas, **conclude** whether burning methane as a fuel would have any influence on atmospheric CO_2 levels. **Explain** your conclusion.

25. Biomass is plant matter such as trees, grasses, and agricultural crops. Conduct research on using biomass as a fuel source (biofuel). Then, write a unified response addressing the following aspects of using biofuel.
- **Describe** how electricity is generated from biofuel.
- **Determine** what proportion of electric power production in Canada comes from biomass energy. **Summarize** the potential for increasing the amount of electricity produced by biomass.
- **Compare** the costs and benefits of producing automobile fuel from biomass with those of producing fuel from petroleum.

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chapter 7

Cellular Respiration

In this chapter

- Exploration: Clothespins and Muscle Fatigue
- Web Activity: ATP in Action
- Chemistry Connection: Combustion of Glucose
- Web Activity: Respiration in Motion
- Investigation 7.1: Measuring Oxygen Consumption in Germinating Seeds
- Mini Investigation: Facultative Microbes
- Explore an Issue: Aerobic versus Anaerobic Waste Treatment
- Mini Investigation: Metabolic Poisons
- Career Connections: Food Scientist; Kinesiologist

As she skated into the final stretch, speed skater Cindy Klassen dug deep and poured on a final surge of energy to win the women's 1500-m event at the 2006 Winter Olympic Games in Turin. Her winning time of 1 min, 55.27 sec. didn't beat her own world-record time of 1 min, 51.79 sec., which she had set a few months earlier. Klassen won five medals at the games, tying the record for most medals won at an Olympics by a speed skater and breaking the record for most medals won by a Canadian at a single Olympic games.

Klassen's exceptional athletic ability was honed to the elite level through extensive training at Calgary's Olympic Oval. Coaches and exercise physiologists looked at every aspect of Klassen's physical performance and technique, trying to shave seconds off her times. To do this, they had to understand the body's energy demands at the cellular level. Cellular respiration is the process cells use to release energy needed for all kinds of work, including muscle contraction. There are two types of cellular respiration: aerobic respiration and anaerobic respiration. During a race, a speed skater's cells are likely to use both types. In this chapter, you will learn the biochemical steps involved in these processes and how these processes are essential for normal people doing everyday activities, not just for Olympic athletes.

STARTING Points

Answer these questions as best you can with your current knowledge. Then, using the concepts and skills you have learned, you will revise your answers at the end of the chapter.

1. (a) What do organisms do with the oxygen they absorb from the air?
(b) What is the source of carbon in the carbon dioxide excreted by these organisms?
(c) Why is carbon dioxide excreted?

2. (a) Why do bakers add yeast to flour and water when making bread?
(b) When yeast is added to grape juice at room temperature, vigorous bubbling occurs. What gas produces the bubbles?
(c) After a while, the bubbling stops. Why does it stop?
(d) What type of beverage is produced by this process?
(e) What is the name of this process?

3. (a) After a long, hard run, your muscles feel sore and stiff. What is the cause of these symptoms?
(b) Why do you pant at the end of the run?

Figure 1
Cindy Klassen started out as a hockey player before taking up speed skating. Both of these activities place great energy demands on the body.

Exploration — Clothespins and Muscle Fatigue

Automobiles and machines must be supplied with gasoline or electricity as a source of energy before they can move. Your muscles require energy in the form of ATP to contract. Muscles can produce ATP by using oxygen (aerobic respiration) or not using it (anaerobic respiration). Anaerobic respiration in muscle cells produces lactic acid. When muscles do a lot of work quickly, lactic acid buildup reduces their ability to contract until exhaustion eventually sets in and contraction stops altogether. This is called muscle fatigue.

Materials: clothespin, timer

- Hold a clothespin in the thumb and index finger of your dominant hand.
- Count the number of times you can open and close the clothespin in a 20 s period while holding your other fingers straight out. Make sure to squeeze quickly and completely to get the maximum number of squeezes for each trial.
- Repeat this process for nine more 20 s periods, recording the result for each trial in a suitable table. Do not rest your fingers between trials.
- Repeat the procedure for the nondominant hand.

(a) Prepare a suitable graph of the data you collected.
(b) What happened to your strength as you progressed through each trial?
(c) Describe how your hand and fingers felt during the end of your trials.
(d) What factors might cause you to get more squeezes (to have less fatigue)?
(e) Were your results different for the dominant and the nondominant hand? Explain why they would be different.
(f) Your muscles would probably recover after 10 min of rest to operate at the original squeeze rate. Explain why.

7.1 The Importance of Cellular Respiration

As you have learned, photosynthesis converts light energy into chemical energy via a series of complex chemical reactions that form a variety of intermediate and final energy-rich molecules. These molecules serve a variety of different energy-related functions within cells.

The primary function of photosynthesis is to convert solar energy into glucose molecules. The glucose molecules may be used immediately. Glucose may then be used immediately, transported to other cells, stored for a medium-term, or used to synthesize molecules that can store energy long-term. Plant cells synthesize starch for long-term storage, by joining many glucose molecules together. Animal and fungal cells link together glucose molecules obtained from their food to form the storage compound glycogen.

When cells require energy for a particular process, it must be supplied in the more directly usable form of ATP. This is the role of cellular respiration. The cells of both animals and plants release the energy stored in the bonds of glucose molecules through the process of cellular respiration. Recall that the process of cellular respiration can be summarized by this equation:

$$\text{glucose} + \text{oxygen} \rightarrow \text{carbon dioxide} + \text{water} + \text{energy}$$
$$C_6H_{12}O_6(s) + O_2(g) \rightarrow CO_2(g) + H_2O(l) + \text{energy}$$

As we saw with photosynthesis, this equation includes only the compounds at the beginning and end of the process. It is the intermediate products that are used by the cells. In cellular respiration, the intermediate products include NADH, $FADH_2$, and ATP.

NADH an electron carrier, donates electrons in cellular processes

NAD^+ an electron carrier, accepts electrons in cellular processes

$FADH_2$ an electron carrier, donates electrons in cellular processes

FAD^+ an electron carrier, accepts electrons in cellular processes

NADH is the reduced form of **NAD^+** (nicotinamide adenine dinucleotide). **$FADH_2$** is the reduced form of **FAD^+** (flavin adenine dinucleotide). Like NADPH and $NADP^+$ in photosynthesis, these compounds serve as electron carriers. Their role is to transfer electrons through oxidation–reduction reactions. Recall that in an oxidization reaction, electrons are lost and in a reduction reaction, electrons are gained. The transfer of electrons releases energy that can be used in cellular respiration and other cellular processes.

The transfer of electrons from one reactive atom to another produces more stable ions or compounds. The fact that the products have less energy than the reactants indicates that energy is released during the oxidation reaction. This energy can be used to make ATP. **Figure 1** on the next page shows how the energy from an oxidation–reduction reaction is used to attach phosphates to ADP. The product, ATP, is a high-energy compound.

Each time electrons are transferred in oxidation–reduction reactions, energy is made available for the cell to make ATP. Electron transport chains shuttle electrons from one molecule to another. For example, the oxidizing agent NAD^+, along with H^+ remove high-energy electrons from organic molecules and form NADH. It then transfers these electrons to energy releasing chemical pathways. The energy released in these pathways is transferred to ADP and P_i to form ATP.

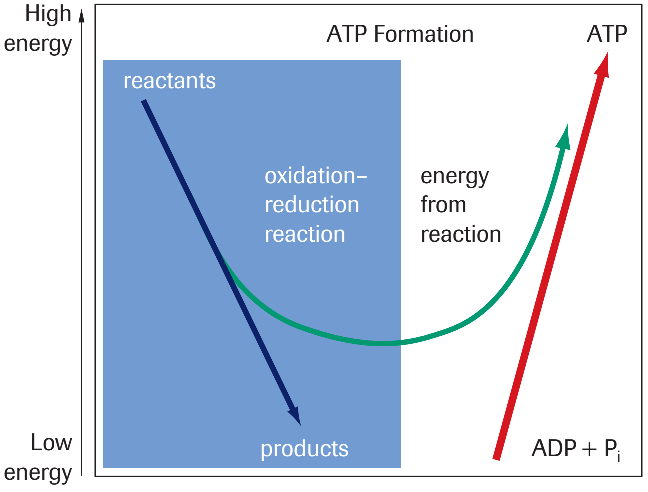

Figure 1
The energy released from the oxidation–reduction reaction is used to attach a free phosphate to ADP to make ATP. Note that ATP is a high-energy compound. The oxidation–reduction reaction could be the transfer of electrons from high-energy compounds such as when NADH is oxidized to form NAD^+ and H^+.

Practice

1. What is the primary function of cellular respiration?
2. How do the oxidation and reduction reactions in electron transfer help to form ATP?

Energy, Cells, and ATP

The energy demands for most cellular processes are supplied by the energy stored in ATP. These energy demands are very diverse. Some, such as chromosome movement in cell division, occur in virtually all living cells, and others, such as bioluminescence (the production of light) occur only in highly specialized cells in a few organisms. These energy demands are not trivial. It is estimated that a typical human cell contains approximately one billion molecules of ATP. These are continuously broken down into ADP and P_i as they release energy to do work, and are then reformed only to be used again.

Active transport (**Figure 2**) can be used to move substances either into or out of the cell. The carrier proteins are often referred to as "pumps." Various types of active transport pumps are found in the membranes of different cells. Potassium and sodium ions are moved into and out of cells by a pump known as the **sodium–potassium pump** (**Figure 3**, next page). Without this pump, nerve cells and muscle cells could not function properly. Other substances, such as vitamins, amino acids, and hydrogen ions are also actively transported across membranes by specialized carrier proteins. All of these pumps require energy from ATP to operate.

active transport the movement of substances through a membrane against a concentration gradient using membrane-bound carrier proteins and energy from ATP

sodium–potassium pump an active-transport mechanism that pumps sodium and potassium ions into and out of a cell

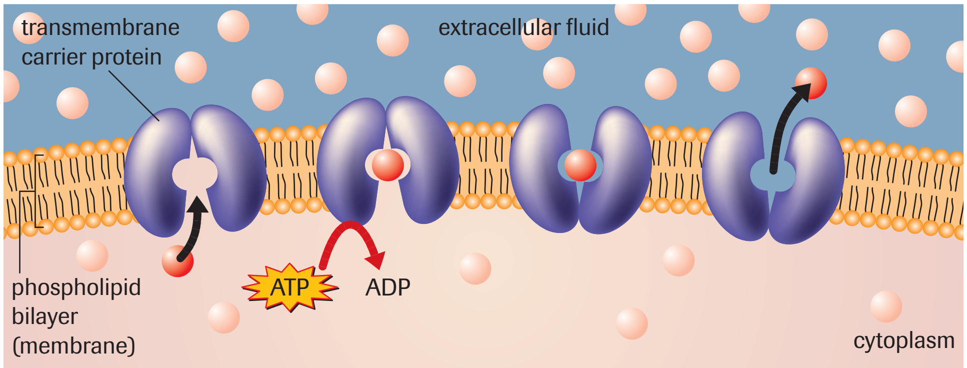

Figure 2
Active transport. The molecule to be transported attaches to an open binding site on one side of the carrier protein. ATP is converted to ADP on the carrier protein and releases energy. The energy causes a change in the shape of the protein that carries the solute to the other side of the membrane.

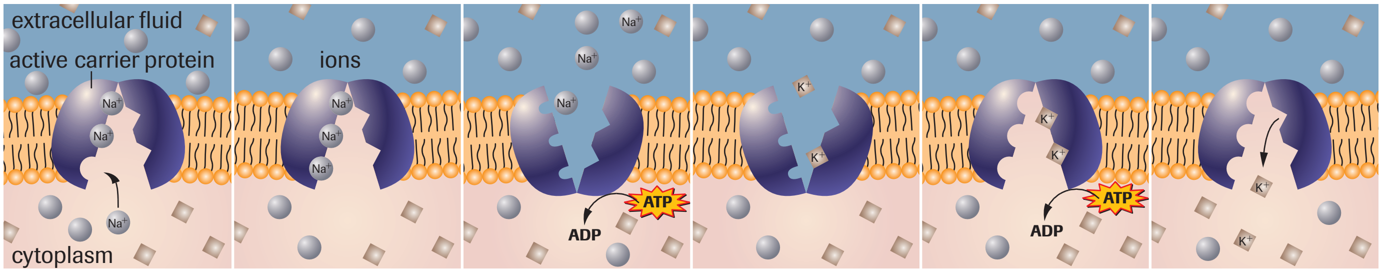

Figure 3
The energy of ATP is used to actively transport three sodium ions out of a cell for every two potassium ions that are transported into the cell.

Another critical use of ATP is that of large-scale motion. In order for you to move, your muscles must contract. The process of muscle contraction involves two different protein molecules sliding past each other. The energy from ATP is used to change the shape of one of the molecules resulting on it pulling on the other. This general process is responsible for all the movements of contractile fibres. (Muscle physiology is covered in detail in Chapter 9.)

Most processes that require ATP energy can be placed in one of categories in **Table 1**.

Table 1 Uses of ATP Energy

Functions requiring ATP	Role of ATP	Examples
motion	• causes various specialized fibres within cells to contract causing movement of the cell or movements within the cell	• chromosome movements during cell division • movement of organelles such as contractile vacuoles emptying • cytoplasmic streaming • formation of pseudopods in lymphocytes or in amoebas • beating of cilia and flagella such as in sperm cells or in certain single-celled organisms
	• causes muscle fibres to contract	• contraction of skeletal, smooth, and cardiac muscles
transport of ions and molecules	• powers active transport of molecules against a concentration gradient across a membrane	• sodium–potassium pump • hydrogen ion pump
building molecules	• provides the energy needed to build many large molecules	• joining amino acids in protein synthesis • Building new strands of DNA during DNA replication
switching reactions on or off	• alters the shape of a molecule, which alters the function of the molecule	• switches certain enzymes on or off
bioluminescence	• reacts with a molecule called luciferin and oxygen	• produces light in some light-generating species such as glow-worms and fireflies

WWW **WEB Activity**

Simulation—ATP in Action

Follow the Nelson links to view animations of various cellular processes requiring ATP energy. Briefly explain each process and indicate the importance of the process to the organism, and how ATP is involved in the process. You may wish to include a labelled sketch of the process.

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Glucose and ATP

All cells use energy from ATP molecules to meet their metabolic energy needs. However, ATP molecules are not abundant in food and provide a relatively small amount of energy per molecule. Molecules with a higher energy content are therefore useful for both long-term storage of chemical energy and for bulk transporting of chemical energy within cells and multicellular organisms. Carbohydrates, most notably in the form of glucose, are the most usable source of energy. Glucose, along with oxygen, is one of the substrates of cellular respiration. During cellular respiration, some of the energy in glucose is converted to ATP.

A useful analogy for the relationship between ATP, glucose, and other energy-rich molecules is that of money. In our analogy, a cell is like a large factory in which all operations are performed by vending machines that only accept one-dollar coins. In order to perform any task (any cellular action) within the factory, one must insert one or more one-dollar coins into a vending machine. In real cells, the one-dollar coins are analogous to ATP molecules. Virtually all processes conducted by cells use ATP molecules, and only ATP molecules, as their immediate energy source.

In contrast, a glucose molecule contains approximately 100 times as much energy as an individual ATP molecule, but this energy cannot be directly used by the cell. It is like a $100 bill in our cell factory. It is certainly valuable, but must be exchanged for coins before it can be used to operate the vending machines. Similarly, in real cells, the energy content of glucose and other energy-rich molecules can be exchanged or converted into the energy of numerous ATP molecules for the running of cellular activities.

Glucose (**Figure 4**), a simple sugar or monosaccharide, is well suited to its role as a convenient energy supply molecule. Glucose is our "blood sugar." It has a high energy content and is relatively small and highly soluble. These latter two properties make glucose ideal for transportation within and between cells, and throughout the body.

CAREER CONNECTION

Food Scientist

Food scientists research and develop new and improved methods of food processing, preserving, and packaging. Healthy and safe food products must be continually tested for nutritional value and high quality, so food scientists are essential in food inspection and monitoring programs.

Find out how you might become a food scientist.

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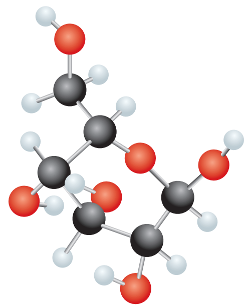

Figure 4
A glucose molecule

Practice

3. Active transport involves carrier proteins imbedded in the membranes of cells. How do these carrier proteins use ATP to transport molecules across the membrane?
4. How is ATP used in muscle contraction?
5. One glucose molecule has 100 times more stored energy than one ATP molecule. Explain why can't cells use glucose to run their processes.

Releasing Energy

During respiration, the chemical bonds of reactant food molecules are broken and new bonds are formed in the resulting chemical products. It always takes energy to break chemical bonds, and energy is always released when new bonds form. In simple terms, respiration is an energy-releasing process because more energy is released during the formation of product molecules than is consumed to break apart the reactant molecules (**Figure 5** on page 208).

The energy released by cellular respiration is used to synthesize ATP molecules to be used as the energy currency within the cell. The fundamental role of cellular respiration is to transfer the energy content of food molecules into the energy content of ATP.

Because food molecules such as glucose have a relatively large energy content, a single molecule can be used to form many lower-energy molecules. In our analogy, this is like exchanging the high-energy content of a $100 bill for the energy content of many one-dollar coins. Unlike a simple banking machine, however, the process of cellular respiration is not 100 % efficient. In fact, it is estimated that, at best, only 36 % of the

DID YOU KNOW?

Breaking Chemical Bonds

Energy is only released when new chemical bonds form. Similarly, energy is always required (used) when bonds are broken. In the case of ATP, energy is released when the phosphate group is removed because new bonds form between the phosphate group and other chemicals involved in the reaction. This is the important source of energy available to the cell.

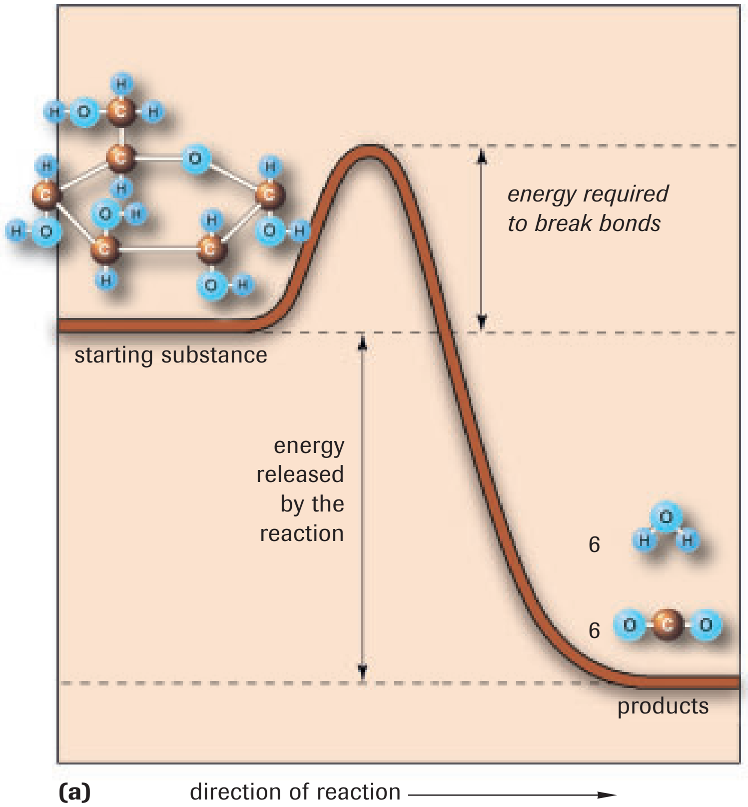

Figure 5
Energy is needed to break the bonds. The energy that is released is the energy from bond formation. The photo shows glucose burning. The high-energy compound, glucose, is converted to low-energy compounds, carbon dioxide, and water.

energy content of a single glucose molecule is converted into the energy of ATP; the remaining 64 % is released as heat. This is analogous to receiving $36 in one-dollar coins in exchange for a $100 bill.

An efficiency of 36 % may not seem very impressive, but keep in mind that cellular respiration involves many complex chemical pathways within cells. For comparison, high-performance racecar engines are slightly less efficient. In these engines only 30 % to 34 % of the energy from fuel combustion is converted to forward motion. The remaining 66 % to 70 % is lost as waste thermal energy. Typical automobiles driven by the public achieve efficiencies of only 25 % to 30 %.

The thermal energy is not waste for all organisms. While the vast majority of living species do not use this thermal energy, two small but significant groups of organisms use it to maintain a constant body temperature. These are warm-blooded organisms (birds and mammals) a group to which we belong. Your body's warmth is a direct product of the inefficient conversion of food energy to ATP energy.

Two Types of Cellular Respiration

While the goal of respiration is a simple one—the conversion of stored food energy into the usable energy of ATP—the process is not. Like photosynthesis, the chemical pathways of respiration are complex and involve many intermediate stages and molecules. A major variable that influences and limits the available chemical pathways of cellular respiration is the presence or absence of oxygen gas.

aerobic cellular respiration the set of reactions that takes place in the cell in the presence of oxygen and releases energy stored in glucose

Aerobic cellular respiration takes place in the presence of oxygen and involves the complete oxidation of glucose. The end products of aerobic cellular respiration are carbon dioxide gas, water, and 36 ATP molecules. Aerobic cellular respiration involves four stages.

Stage 1: glycolysis
Stage 2: pyruvate oxidation
Stage 3: the Krebs cycle
Stage 4: the electron transport chain and chemiosmosis

This equation summarizes aerobic respiration:

$$C_6H_{12}O_6 + 6\,O_2 + 36\,ADP + 36\,P_i \rightarrow 6\,CO_2 + 6\,H_2O + 36\,ATP$$

glucose + oxygen + ADP + inorganic phosphate → carbon dioxide + water + ATP

Anaerobic cellular respiration takes place in the absence of oxygen, and glucose is not completely oxidized. There are two main types of anaerobic cellular respiration, which have different end-products. Both types of cellular respiration occur in two stages that take place in the cytoplasm of the cell.

anaerobic cellular respiration the set of reactions that takes place in the cell in the absence of oxygen and releases energy stored in glucose

Stage 1: glycolysis
Stage 2: fermentation

The equations below summarize the two types of anaerobic cellular respiration that occur in eukaryotes:

$$C_6H_{12}O_6 + 2\,ADP + 2\,P_i \rightarrow 2\,C_2H_5OH + 2\,CO_2 + 2\,ATP$$

glucose + ADP + inorganic phosphate → ethanol + carbon dioxide + ATP

$$C_6H_{12}O_6 + 2\,ADP + 2\,P_i \rightarrow 2\,C_3H_6O_3 + 2\,ATP$$

glucose + ADP + inorganic phosphate → lactic acid + ATP

Notice that the first stage for both aerobic and anaerobic respiration is glycolysis! Also, from the three summary equations, you can see that aerobic respiration produces many more ATP molecules than do either type of anaerobic respiration. You will find out more about these processes in the rest of the chapter.

+ EXTENSION

Where Pathways Start and Finish

View this brief animation comparing anaerobic and aerobic respiration. Where does each process occur in the cell, and how much ATP does each process produce?

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SUMMARY The Importance of Cellular Respiration

- Cells cannot use high-energy molecules, such as glucose, directly. Cellular respiration converts glucose into energy-containing molecules the cells can use directly, such as ATP.
- Cells use ATP for their immediate energy needs.
- Aerobic cellular respiration takes place in the presence of oxygen and produces 36 ATP molecules per glucose molecule.
- Anaerobic respiration takes place in the absence of oxygen and produces 2 ATP molecules per glucose molecule.

Section 7.1 Questions

1. What are the characteristics of glucose that make it well suited as an energy supply molecule within our bodies?
2. The conversion of glucose energy to ATP energy is less than 50 % efficient. In what way do birds and mammals take advantage of this inefficiency?
3. Briefly describe one cellular process that involves the use of active transport. How is ATP involved in this process?
4. Why is cellular respiration necessary?
5. What are the four stages of aerobic respiration?

7.2 Glycolysis

In the previous section, you found out that cells may undergo two types of cellular respiration, depending on whether oxygen is available. Aerobic cellular respiration takes place in the presence of oxygen, and anaerobic cellular respiration takes place in the absence of oxygen. However, both types of cellular respiration begin with exactly the same process, called **glycolysis**.

glycolysis a process for harnessing energy in which a glucose molecule is broken into two pyruvate molecules in the cytoplasm of a cell

Recall that glucose is a high-energy molecule that cannot be used directly by the cell. Glycolysis is Greek for "sugar splitting," and this accurately describes what happens to glucose during this first stage of cellular respiration. The carbon backbone of glucose is essentially split in half. As you can see in **Figure 1**, glucose is a six-carbon sugar. At the end of glycolysis, glucose has been converted to a three-carbon sugar called pyruvate.

Although it occurs in both types of cellular respiration, glycolysis itself is an anaerobic process: it does not require oxygen. Glycolysis takes place in the cytoplasm of the cell. There are ten reactions in glycolysis, each of which is catalyzed by a specific enzyme in the cytoplasm. During these reactions, two ATP molecules are used and four ATP molecules are produced. Glycolysis therefore produces a net total of two ATP molecules. Glycolysis also produces two $NADH^+$ ions.

EXTENSION

Glycolysis
In this animation, you can see all the intermediate molecules that form as glycolysis converts one glucose molecule to two pyruvate molecules, and how ATP and $NADH^+$ are formed.

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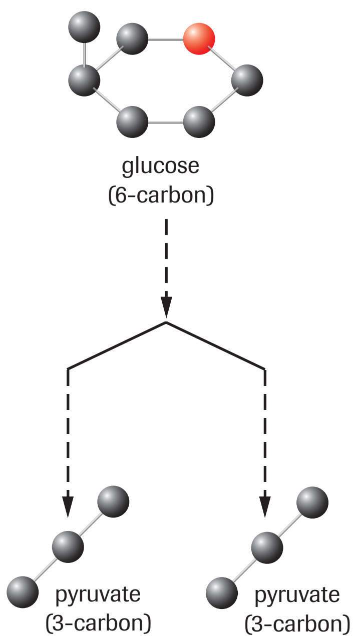

Figure 1
In a series of reactions called glycolysis, a 6-carbon glucose molecule is split into two 3-carbon pyruvate molecules. (For simplicity, the side-group oxygen and hydrogen atoms are not illustrated here.)

Figure 2 on the next page summarizes the reactions of the glycolytic pathway. The long arrow represents the entire pathway of chemical steps that occur during glycolysis. The emphasis is on the key features of this process; the numerous intermediate chemical compounds and reactions are not shown in detail.

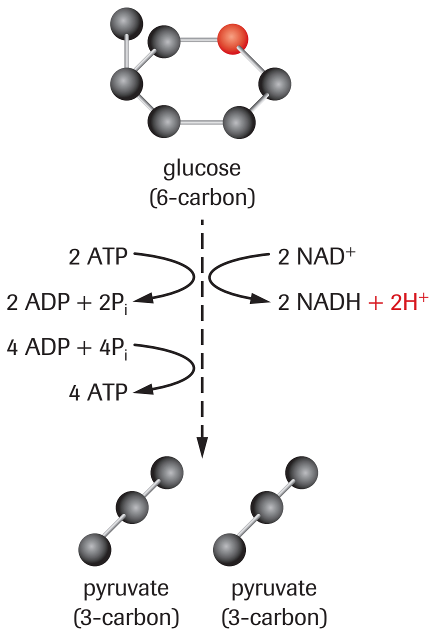

Figure 2
Summary of the glycolytic pathway. Glycolysis is a series of ten chemical reactions, the details of which are not shown.

As you study **Figure 2**, note the following key events:

- Two ATP molecules are used in the first stages of glycolysis. This represents an "investment of energy."
- During glycolysis, oxidation–reduction reactions occur in which two positively charged NAD^+ ions remove hydrogen atoms from the pathway to form two NADH molecules and release two H^+ ions into the cytoplasm.
- In the later stages of glycolysis, enough energy is released to join four ADP molecules with four P_i molecules to form four ATP molecules.
- When glycolysis is complete, the cell has consumed a single glucose molecule and produced two ATP molecules, two NADH molecules, and two pyruvate molecules.
- These ATP molecules are available to supply energy for cellular functions.

Note that the original glucose molecule contained 24 atoms (six C, twelve H, and six O). Of these, six carbon, eight hydrogen, and six oxygen atoms are now held in the two pyruvate molecules ($C_3H_4O_3$). The remaining four high-energy hydrogen atoms are in the form of two NADH molecules and two H^+ ions. **Table 1** lists the reactants and products of glycolysis.

Table 1 The Reactants and Products of Glycolysis

Reactants	Products
glucose	2 pyruvate
2 NAD^+	2 NADH
2 ATP	2 ADP
4 ADP	4 ATP

The net equation for glycolysis is

$$1 \text{ glucose} + 2 \text{ ADP} + 2 \text{ P}_i + 2 \text{ NAD}^+ \rightarrow 2 \text{ pyruvate} + 2 \text{ ATP} + 2 \text{ NADH} + 2\text{H}^+$$

EXTENSION

ATP and Glycolysis

Listen to this Audio Clip to find out why ATP must be a reactant in glycolysis, even though the role of this process is to produce energy for a cell.

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By itself, glycolysis is not a highly efficient energy-harnessing mechanism. One glucose molecule contains over 90 times as much available energy as a cell obtains when it uses a single ATP. This means that the process of glycolysis transfers only about 2.2 % of the free energy available in glucose to ATP. Some of the energy is released as thermal energy during the process, but the vast majority is still trapped in the two pyruvate and two NADH molecules. The 2.2 % conversion efficiency value applies to glycolysis only; it does not take into consideration the possibility of obtaining additional ATP by further processing pyruvate and NADH in the remaining stages of aerobic respiration.

Some simple single-celled microorganisms can use glycolysis for all their energy needs. However, glycolysis yields only two ATP molecules from each glucose molecule processed. This is not enough to satisfy the energy needs of most multicellular organisms. Nevertheless, all organisms, large and small, multicellular or not, carry out glycolysis either as their only source of ATP or as the first part of a more productive energy-yielding process, such as aerobic respiration.

WWW WEB Activity

Simulation—Respiration in Motion

Respiration involves many reactions and processes that can be difficult to visualize. In this activity, you will explore some animations and act out a specific step for the rest of the class. In groups, follow the Nelson Web links and view various animations of respiration pathways. Your group will then be assigned a specific step or process and will create a short skit. As each group acts out a skit for the class, students will guess which step of respiration is being modelled. Your teacher will provide you with suggestions and rules.

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SUMMARY Glycolysis

- Glycolysis occurs in the cytoplasm. It produces two 3-carbon pyruvate molecules from a 6-carbon glucose molecule. Glycolysis produces two ATP (net) and two NADH.
- The efficiency of glycolysis is only 2.2 % with most of the original energy of the glucose remaining in the pyruvate and NADH molecules.
- The net equation for glycolysis is

$$1 \text{ glucose} + 2 \text{ ADP} + 2 \text{ P}_i + 2 \text{ NAD}^+ \rightarrow 2 \text{ pyruvate} + 2 \text{ ATP} + 2 \text{ NADH} + 2\text{H}^+$$

Section 7.2 Questions

1. Write an overall chemical equation for glycolysis.
2. (a) What does *glycolysis* mean?
   (b) List the final products of glycolysis.
3. As a result of glycolysis, only a small portion of the energy of glucose has been converted to ATP. In what form is the rest of the usable energy found at this stage of the process?

Aerobic Cellular Respiration 7.3

Under aerobic conditions (oxygen gas is available), cells will undergo aerobic cellular respiration. The end products of aerobic cellular respiration are carbon dioxide gas, water, and relatively large numbers of ATP molecules. Recall that aerobic cellular respiration has four stages. These are:

Stage 1: glycolysis—a ten-step process occurring in the cytoplasm

Stage 2: pyruvate oxidation—a one-step process occurring in mitochondria

Stage 3: the Krebs cycle—an eight-step cyclical process occurring in mitochondria

Stage 4: the electron transport chain and chemiosmosis (oxidative phosphorylation)—a multi-step process occurring in the inner mitochondrial membrane

In the previous section, you looked at Stage 1, glycolysis, which takes place in the cytoplasm. In this section, you will learn about the last three stages, which all take place within mitochondria.

CHEMISTRY CONNECTION

Combustion of Glucose

Aerobic respiration can be thought of as complete combustion, since the products are carbon dioxide, water, and energy. Your chemistry textbook has more information on combustion reactions.

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INVESTIGATION 7.1 *Introduction*

Measuring Oxygen Consumption in Germinating Seeds

Plant seeds contain living embryos that require energy to carry out the functions of life. When they germinate, they experience high rates of growth and cell division. What happens to a plant seed's rate of energy metabolism when it germinates and starts to grow? Do germinating seeds absorb or release thermal energy?

Report Checklist

○ Purpose	○ Design	● Analysis
○ Problem	○ Materials	● Evaluation
○ Hypothesis	○ Procedure	● Synthesis
● Prediction	● Evidence	

Investigation 7.1 provides you with an opportunity to conduct controlled experiments on the relationship between growth and the rate of metabolic activity.

To perform this investigation, turn to page 229.

Mitochondria

Mitochondria (singular: mitochondrion) are round or sausage-shaped organelles that are usually scattered throughout a cell's cytoplasm. These vital organelles specialize in the production of large quantities of ATP, the main energy-carrying molecule in living cells. The processes that produce ATP in mitochondria cannot proceed without free oxygen.

Mitochondria possess a double membrane composed of a smooth outer membrane and a highly folded inner membrane (**Figure 1**, next page). The outer membrane plays a role similar to that of the cell membrane, but the inner membrane performs many functions associated with cellular respiration. The inner membrane also creates two compartments within the mitochondrion. The **mitochondrial matrix** is a protein-rich liquid that fills the innermost space of a mitochondrion, and a fluid-filled **intermembrane space** lies between the inner and outer membrane. Each of these compartments play a critical role in aerobic respiration.

Figure 2 on the next page illustrates the four stages of respiration and indicates their locations within the cell.

mitochondrion a eukaryotic cell organelle in which aerobic cellular respiration occurs

mitochondrial matrix the fluid that fills the interior space of the mitochondrion

intermembrane space the fluid-filled space between the inner and outer mitochondrial membranes

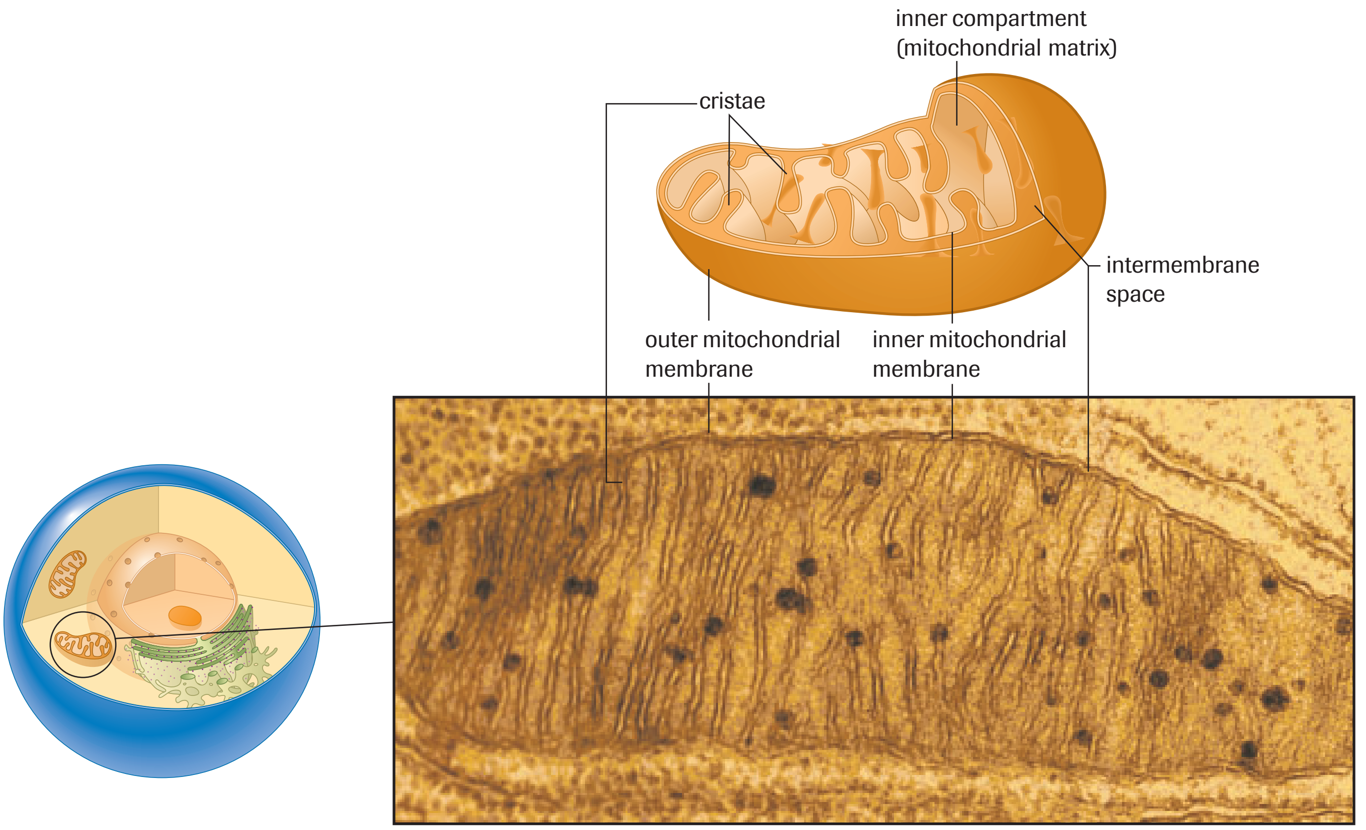

Figure 1
Diagram and transmission electron micrograph of a typical mitochondrion

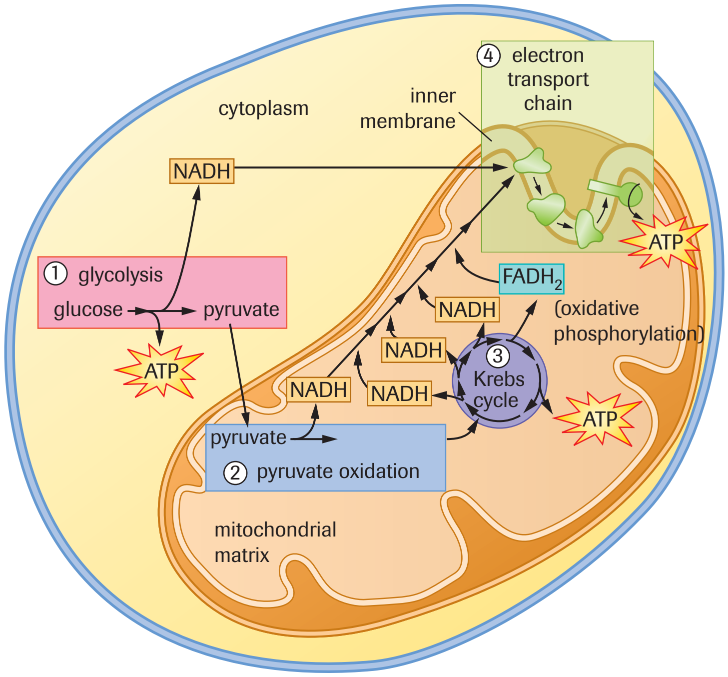

Figure 2
In eukaryotic cells, glycolysis (1) occurs in the cytoplasm (pink). Pyruvate oxidation (2) and the Krebs cycle (3) occur in the mitochondrial matrix (blue and purple respectively). The electron transport chain (4) is embedded in the inner mitochondrial membrane (green).

Stage 2: Pyruvate Oxidation

Recall that by the end of Stage 1, glycolysis, the cell had formed two ATPs, two NADHs and two pyruvate molecules—all in the cytoplasm. Pyruvate oxidation is a chemical pathway that connects glycolysis in the cytoplasm with the Krebs cycle in the mitochondrial matrix (**Figure 2**, previous page). Stage 2 begins when the two pyruvate molecules formed in glycolysis are transported through the two mitochondrial membranes into the matrix. There, the following three changes occur (**Figure 3**):

1. A CO_2 is removed from each pyruvate and released as a waste product. This step is the source of one-third of the carbon dioxide that you breathe out.
2. The remaining 2-carbon portions are oxidized by NAD^+. Each NAD^+ molecule gains two hydrogen ions (two protons and two electrons) from pyruvate, and the remaining 2-carbon compound becomes an acetic acid (acetyl) group. This converts pyruvate to an acetic acid group and transfers high-energy hydrogens to NAD^+.
3. A compound called coenzyme A (CoA) becomes attached to the acetic acid group, forming acetyl-CoA. The acetyl-CoA then enters the next stage of aerobic cellular respiration, the Krebs cycle.

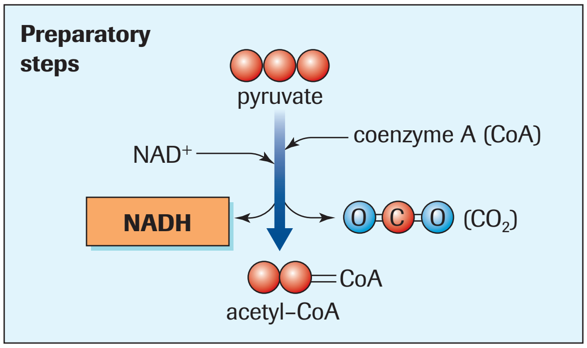

Figure 3
Pyruvate oxidation results in three changes to pyruvate:
1. A CO_2 portion is removed.
2. NAD^+ is reduced by two H atoms.
3. Coenzyme A is attached to the remaining 2-carbon portion (acetyl group).

The two molecules of acetyl-CoA enter the Krebs cycle, while the two molecules of NADH proceed to Stage 4 (electron transport and chemiosmosis). The two CO_2 molecules produced during pyruvate oxidation diffuse out of the mitochondrion and then out of the cell as a low-energy waste product.

Practice

1. What stages of aerobic cellular respiration take place in the mitochondria?
2. What happens to NAD^+ in Stage 2 of aerobic cellular respiration?
3. What is the role of coenzyme A?

Stage 3: The Krebs Cycle

In 1937, Sir Hans Krebs (1900–81), a biochemist working at the University of Sheffield in England, discovered the series of metabolic reactions that became known as the Krebs cycle. He received the 1953 Nobel Prize in Physiology or Medicine for this important discovery. Fritz Albert Lipmann (1899–1986) shared the Nobel Prize with Krebs for his discovery of coenzyme A and the key role it plays in metabolism.

The **Krebs cycle** is an eight-step process, each step catalyzed by a specific enzyme. It is a cyclic process because one of the products of Step 8, is a reactant in Step 1 (**Figure 4**, next page). Key features of the Krebs cycle are outlined in **Table 1**, on the next page.

Krebs cycle a cyclic series of reactions that transfers energy from organic molecules to ATP, NADH, and $FADH_2$, and removes carbon atoms as CO_2

EXTENSION

The Krebs Cycle—Details

In this animation, view the details of the intermediate stages of pyruvate oxidation and the Krebs Cycle. These reactions all take place in the inner compartment of mitochondria.

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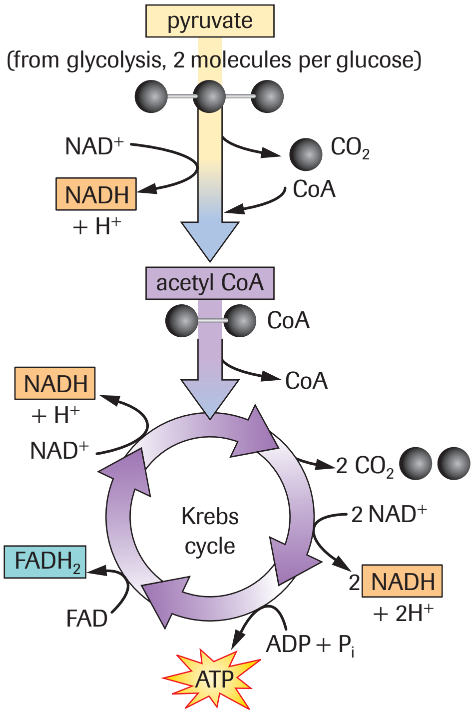

Figure 4
The Krebs cycle begins when acetyl-CoA condenses with oxaloacetate to form citrate. In one turn of the cycle, the two carbon atoms that were originally in a glucose molecule are removed as CO_2, and free energy is transferred to ATP, NADH, and $FADH_2$.

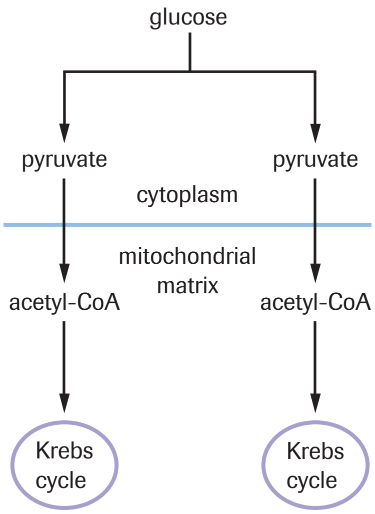

Figure 5

Table 1 Key Features of the Krebs Cycle

• Since two molecules of acetyl-CoA are formed from one molecule of glucose, the Krebs cycle occurs twice for each molecule of glucose processed (**Figure 5**).
• As acetyl-CoA enters the cycle the CoA is released and can be used for the next pyruvate.
• During one complete cycle a total of three NAD^+s and one FAD are reduced to form three NADHs and one $FADH_2$.
• During one complete cycle an ADP and a P_i are combined to form one ATP.
• During one complete cycle two CO_2 molecules are produced. These are released as waste.

Notice that by the end of the Krebs cycle, all six carbon atoms of glucose have been oxidized to CO_2 and released from the cell as metabolic waste. All that is left of the original glucose molecule is some of its free energy in the form of ATP and high-energy NADH and $FADH_2$. NADH and $FADH_2$ now go on to Stage 4 of the process, electron transport and chemiosmosis, where much of their energy will be transferred to ATP.

Stage 4: Electron Transport and Chemiosmosis

NADH and $FADH_2$ eventually transfer the hydrogen atom electrons they carry to a series of compounds, mainly proteins, which are associated with the inner mitochondrial membrane called the electron transport chain (ETC). **Figure 6** on the next page illustrates this process beginning with a single NADH molecule. The NADH gives up two high-energy electrons at the beginning of the ETC. At the same time, it releases an additional

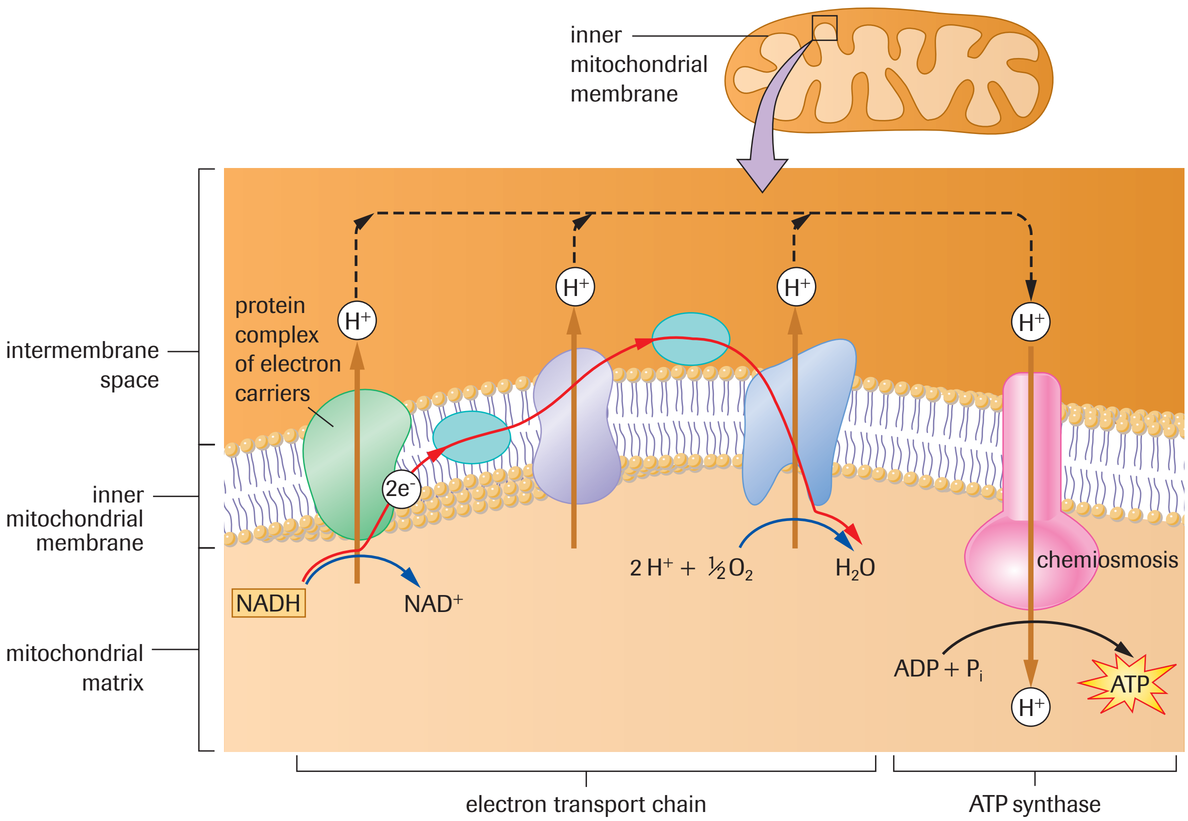

Figure 6
The NADH carries the electrons gained from food to the electron transport chain. As these electrons are passed along carrier molecules, the energy released is used to pump hydrogen ions across the membrane. The electrons are finally accepted by oxygen molecules. Water is the byproduct of the electron transport chain.

H^+ ion into the matrix. The electrons shuttle through the ETC like a baton handed from runner to runner in a relay race. As the electrons move from carrier molecule to carrier molecule in the ETC, they release energy. This energy is used to force a number of H^+ ions from within the mitochondrial matrix across the inner membrane. Each of these ions gains potential energy as they move through proton pumps into the intermembrane space. By the time the two electrons reach the last component of the ETC, they are in a low energy state, having transferred much of their initial energy to the H^+ ions that have been pumped across the inner mitochondrial membrane at three different locations. Oxygen strips the two electrons from the final carrier in the chain and, together with two H^+ ions from the matrix, forms water. As such, oxygen acts as the final electron acceptor in the electron transport process. This final step in the ETC is the reason all aerobic organisms, like humans, must obtain oxygen gas from their environment on a continuous basis.

Note that the ETC is an ongoing process with countless NADHs delivering their electrons to the chain in a continuous flow. $FADH_2$ behaves in a very similar fashion to NADH, delivering its electrons to the ETC. A significant difference however, is that the electrons removed from the $FADH_2$ have a lower energy content and enter the ETC at a different location. The result is that the energy they release is not able to pump as many H^+ ions across the inner mitochondrial membrane.

The electron transport process releases a relatively large quantity of energy. As mentioned earlier, the energy lost by the electron pair during electron transport is used to pump H^+ ions into the intermembrane space. This mechanism converts one form of energy into another—the chemical energy of the electrons is converted to electrochemical potential

DID YOU KNOW?

Cyanide Blocks the Electron Transport Chain

Cyanide prevents oxygen from acting as the final electron acceptor in the electron transport chain. This disruption virtually shuts down ATP production, resulting in coma and death. That is why cyanide is a poison. However, it is not poisonous to all organisms. Some anaerobic bacteria actually live on cyanide—they use it in the same way aerobes use oxygen!

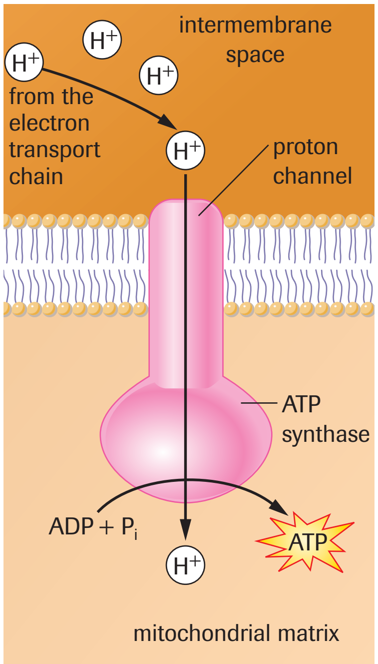

Figure 7
One molecule of ATP is synthesized from ADP and P_i as an H^+ ion passes through the ATPase complex into the mitochondrial matrix from the H^+ reservoir in the intermembrane space.

DID YOU KNOW?

Chemiosmosis

Chemiosmosis was first worked out by Peter Mitchell in 1961. He received the 1978 Nobel Prize in Chemistry for "his contribution to the understanding of biological energy transfer through the formulation of the chemiosmotic theory." Mitchell called the process chemiosmosis because the energy that drives the synthesis of ATP comes from the "osmosis" of protons through a membrane from one compartment into another.

oxidative ATP synthesis the production of ATP from a series of oxidation reactions

energy of an H^+ ion gradient that forms across the inner mitochondrial membrane. Electrochemical potential energy is the type of stored energy possessed by a charged battery. It is caused by an accumulation of charged objects (ions, protons, electrons, etc.) on one side of an insulator. As you are about to learn, this energy is used by cells in a process called chemiosmosis to generate large numbers of ATP!

Chemiosmosis and Oxidative ATP Synthesis

The production of ATP within mitochondria is very similar to the ATP synthesis that occurs across the thylakoid membranes in chloroplasts. The H^+ ions that accumulate in the intermembrane space of the mitochondrion during electron transport create an electrochemical gradient that stores energy. This gradient is caused by a higher positive charge in the intermembrane space than in the matrix. The intermembrane space essentially becomes an H^+ reservoir because the inner mitochondrial membrane is virtually impermeable to H^+ ions. The electrochemical gradient creates a potential difference (voltage) across the inner mitochondrial membrane similar to that in a chemical cell or battery. Unable to diffuse through the membrane, the protons are forced to pass through special proton channels associated with the enzyme ATP synthase (ATPase). The energy stored in the electrochemical gradient produces a force that moves H^+ ions through an ATPase complex. As H^+ ions move through the ATPase complex, the energy that is released drives the synthesis of ATP from ADP and inorganic phosphate (P_i) in the matrix (**Figure 7**).

Thus, some of the energy in the pumping of H^+ ions across the membrane is harvested as chemical potential energy in ATP. The electrons removed from a single NADH pump enough H^+ ions across the inner membrane to generate three ATPs, while the electrons from a single $FADH_2$ pump enough H^+ ions across the membrane to yield two ATPs.

Electron transport followed by chemiosmosis is the last stage of the oxidative phosphorylation process that began with the reduction of NAD^+ and FAD with hydrogen atoms from the original glucose molecule. The continual production of ATP by this method is dependent on the establishment and maintenance of an H^+ reservoir. This condition requires the continual movement of electrons through the ETC, which, in turn, is dependent on the availability of oxygen to act as the final electron acceptor. Oxygen is needed to keep the electrons flowing through the ETC. Electrons are "pulled down" the chain in an energy-yielding "fall," similar to gravity pulling a skydiver down toward Earth's surface. The energy released in the fall keeps H^+ ions moving into the H^+ reservoir so that they can "fall back" into the matrix and drive the synthesis of ATP. Since the energy released in the ETC results from a series of oxidation reactions, the end result—the production of ATP—is often referred to as **oxidative ATP synthesis**.

After ATP molecules are formed by chemiosmosis, they are transported through both mitochondrial membranes into the cytoplasm, where they are used to drive processes requiring energy such as movement, active transport, and synthesis reactions throughout the cell.

As you can see, the three stages of aerobic respiration (pyruvate oxidation, the Krebs cycle, and electron transport and chemiosmosis) are all linked to one another and are all dependent on glycolysis for the production of pyruvate. Note that the last stage of the energy transferring processes—chemiosmosis and electron transport—are dependent on the availability of electrons (from food such as glucose) and oxygen (for its ability to act as a final electron acceptor).

Practice

4. Describe the function of NAD^+ and FAD in aerobic cellular respiration.
5. What are the final products of aerobic cellular respiration?
6. As a result of glycolysis, pyruvate oxidation, and the Krebs cycle, only a small portion of the energy of glucose has been converted to ATP. In what form is the rest of the usable energy found at this stage of the process?

The Aerobic Respiration Energy Balance Sheet

How much energy was transferred from glucose to ATP in the entire aerobic respiration process? We may calculate two values in answer to this question: a theoretical value and an actual value. Although the actual value gives a more realistic total, it too varies according to the type of cell and various environmental conditions. **Figure 8** summarizes the theoretical yield of 36 ATP and its sources. Note that the NADHs produced during glycolysis are not able to generate three ATP each. Instead they transfer their electrons to FADs which are then used in the ETC to produce two ATPs each.

Numerous experiments have demonstrated that under normal conditions cells are not able to achieve this theoretical maximum yield of 36 ATP per glucose. Instead, cells have an actual yield of approximately 30 ATP per glucose molecule. Recall that glycolysis was only 2.2 % efficient. By comparison, even at this reduced level, aerobic respiration is over 32 % efficient! A dramatic improvement and a compelling reason that so many organisms utilize oxygen gas to release energy from their food.

EXTENSION

Effect of Hypothermia (Reduced Body Temperature) on the Respiration Rate of a Ground Squirrel

Many animals have very low metabolic rates during winter months. In this Virtual Biology Lab, you will manipulate the body temperature of a ground squirrel to test how this affects its rate of aerobic cellular respiration.

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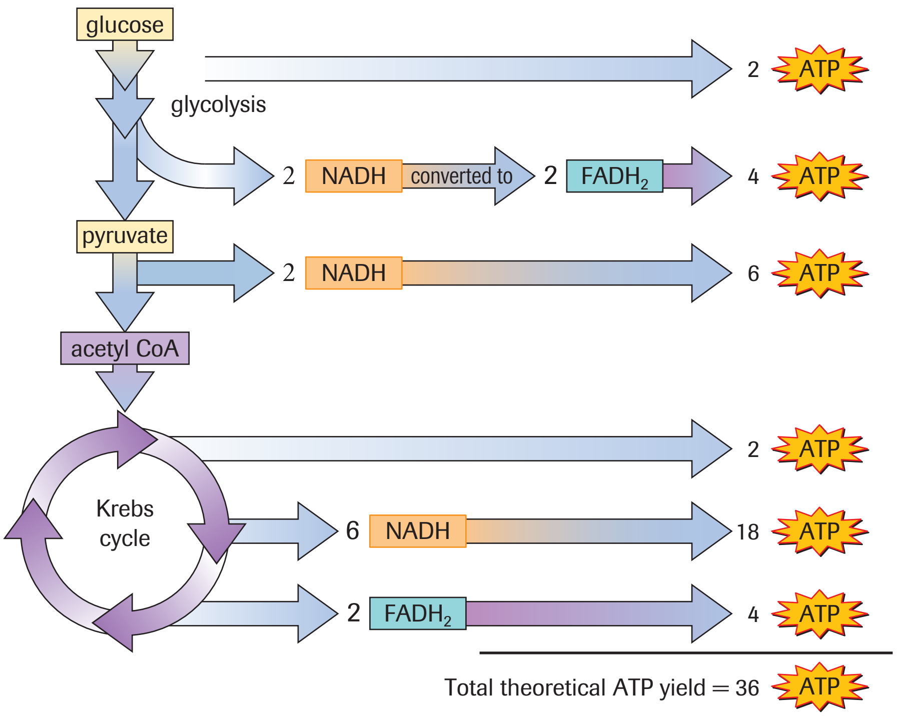

Figure 8
Theoretical ATP yield from the aerobic respiration of one glucose molecule

SUMMARY Aerobic Cellular Respiration

- Aerobic cellular respiration involves four stages: glycolysis, pyruvate oxidation, the Krebs cycle, and electron transport and chemiosmosis.
- Pyruvate oxidation occurs in the mitochondria. In the process, a CO_2 portion is cleaved from pyruvate and removed from the cell as waste. The remaining 2-carbon acetyl group attaches to coenzyme A to produce acetyl-CoA. In this reaction, two NADH and two CO_2 are formed (one for each of the two pyruvate molecules).
- The Krebs cycle occurs in the mitochondrial matrix. The two carbon atoms introduced by acetyl-CoA are removed as two CO_2. One ATP, one $FADH_2$ and three NADH are produced.
- The electron transport chain, associated with the inner mitochondrial membrane, transports electrons through a series of reactions that transfers energy to H^+ ions as they are pumped into the mitochondrial intermembrane space. This creates an electrochemical gradient.
- In chemiosmosis, protons move through ATPase complexes embedded in the inner mitochondrial membrane, releasing free energy that drives the synthesis of ATP.
- Oxygen is the final acceptor of electrons that pass through the electron transport chain. If oxygen is not available, the Krebs cycle, electron transport, and chemiosmosis come to a halt.
- The overall equation for aerobic respiration is:

$$\text{glucose } (C_6H_{12}O_6) + 6\ O_2 + 36\ \text{ADP} + 36\ P_i \rightarrow 6\ CO_2 + 6\ H_2O + 36\ \text{ATP}$$

Section 7.3 Questions

1. Arrange the following types of cells in order of increasing number of mitochondria in the cytoplasm: nerve cell, skin cell, fat cell, heart muscle cell. Provide a rationale for your sequence.
2. (a) In eukaryotic cells, where does glycolysis occur?
   (b) What two products of glycolysis may be transported into mitochondria for further processing?
3. Describe two functions that mitochondrial membranes serve in energy metabolism.
4. Why is aerobic cellular respiration a more efficient energy-extracting process than glycolysis alone?
5. (a) What part of a glucose molecule provides electrons in cellular respiration?
   (b) Describe how electron transport complexes set up a proton gradient in response to electron flow.
   (c) How is the energy used to drive the synthesis of ATP?
   (d) What is the name of this process?
   (e) Who discovered this mechanism?
6. (a) Distinguish between an electron carrier and a terminal electron acceptor.
   (b) What is the final electron acceptor in aerobic respiration?
7. Explain how the following overall equation for cellular respiration is misleading:

   $$C_6H_{12}O_6 + 6\ O_2 \longrightarrow 6\ CO_2 + 6\ H_2O$$

8. Explain why CO_2 does not serve as a source of free energy in living systems.
9. (a) Explain the role of $FADH_2$ in the electron transport chain.
   (b) Explain why $FADH_2$ does not generate as many ATP molecules as NADH does.
10. Aerobic cellular respiration stops if no oxygen is present. Explain why.

Anaerobic Cellular Respiration 7.4

Glycolysis allows organisms to obtain energy from nutrients in the absence of oxygen. As you will recall, during glycolysis NAD^+ is converted to NADH. Glycolysis cannot occur without this reaction. Cells possess a limited supply of NAD^+ and, without a mechanism to convert NADH into NAD^+, glycolysis will come to a halt. If glycolysis stops, ATP can no longer be formed and cell death soon follows.

In aerobic organisms, all NADH is converted into NAD^+ in the ETC—a process that requires oxygen. Without oxygen, the ETC cannot operate and, as a result, anaerobic organisms have evolved several ways of recycling NAD^+ and allowing glycolysis to continue. One method involves transferring the hydrogen atoms of NADH to certain organic molecules instead of to the electron transport chain. This process is called fermentation. Bacteria have evolved dozens of different forms of fermentation, but eukaryotes (organisms whose cells contain nuclei, such as humans) primarily use two methods: **alcohol fermentation** and **lactic acid fermentation**.

Both types of fermentation processes occur in only two stages, all within the cytoplasm of the cell. All fermenting organisms perform the same first stage—glycolysis. It is the second stage that is variable, with different organisms using different pathways.

Stage 1: glycolysis—the identical 10-step process used in aerobic respiration

Stage 2: fermentation—recycles some of the products of glycolysis in two different pathways where either carbon dioxide and ethanol (alcohol fermentation) or lactic acid (lactic acid fermentation) are the final waste products

Alcohol Fermentation

In alcohol fermentation, NADHs molecules produced during glycolysis pass their hydrogen atoms to acetaldehyde, a compound formed when a carbon dioxide molecule is removed from pyruvate by the enzyme pyruvate decarboxylase, as shown in **Figure 1**.

+ EXTENSION

Effect of Physical Activity on Scorpion Respiration Rate
In this Virtual Biology Lab, you will modify the amount of muscle activity in a scorpion and observe the effect on respiration rate. Will the animal move from aerobic respiration to anaerobic respiration? How would you be able to tell?

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alcohol fermentation a form of fermentation occurring in yeast in which NADH passes its hydrogen atoms to acetaldehyde, generating carbon dioxide, ethanol, and NAD^+

lactic acid fermentation a form of fermentation occurring in animal cells in which NADH transfers its hydrogen atoms to pyruvate, regenerating NAD^+ and lactic acid

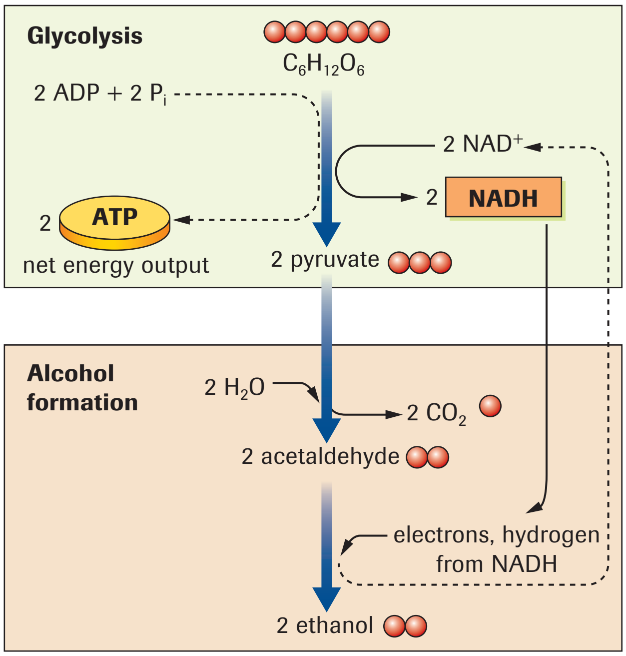

Figure 1
Alcohol fermentation creates ethanol and carbon dioxide from glucose. In the process, NADH is oxidized to NAD^+, allowing glycolysis to continue.

This forms ethanol, the type of alcohol used in alcoholic beverages. This process recycles NAD^+ and so allows glycolysis to continue. The two ATP molecules produced during glycolysis satisfy the organism's energy needs, and the ethanol and carbon dioxide are released as waste products. The overall equation for alcohol fermentation is

$$\text{glucose } (C_6H_{12}O_6) + 2\text{ ADP} + 2\text{ P}_i \rightarrow 2\text{ ethanol } (C_2H_5OH) + 2\text{ CO}_2 + 2\text{ ATP}$$

Figure 2
Alcohol fermentation is used in the production of baked goods and products such as wine, beer, and soy sauce.

Applications of Alcohol Fermentation

Humans have learned ways of making use of these products of fermentation. Alcohol fermentation carried out by yeast (a variety of single-celled fungi) is of great historical, economic, and cultural importance. Breads and pastries, wine, beer, liquor, and soy sauce are all produced using fermentation (**Figure 2**).

Bread is leavened by mixing live yeast cells with starches (in flour) and water. The yeast cells ferment the glucose from the starch and release carbon dioxide and ethanol. Small bubbles of carbon dioxide gas cause the bread to rise (or leaven), and the ethanol evaporates away when the bread is baked. In beer making and winemaking, yeast cells ferment the sugars found in carbohydrate-rich fruit juices, such as grape juice. The mixture bubbles as the yeast cells release carbon dioxide gas and ethanol during fermentation. In winemaking, fermentation ends when the concentration of ethanol reaches approximately 12 %. At this point, the yeast cells die as a result of alcohol accumulation and the product is ready to be consumed as a beverage.

Microbial fermentation is used to make many different food products. **Table 1** lists a few of these foods and the raw materials from which they are made.

Table 1 Sample Food Products Dependent on Microbial Fermentation

Food	Raw material
bread	flour
soy sauce	soya bean
vinegar	alcohol (from fruit or grain fermentation)
chocolate	cacao bean
sauerkraut	cabbage
wine and beer	grapes and barley

Figure 3
Although Louis Pasteur (1822–95) is best known for introducing the process of pasteurization, he also pioneered the vaccines against rabies and anthrax.

While such fermentation products have been produced for centuries, it was not until 1803 that scientists discovered that the yeasts being used in many of these processes were alive. Later, Louis Pasteur (**Figure 3**) provided experimental evidence that yeast was responsible for alcohol fermentation. His work on these processes helped lead him to the monumental discovery that many diseases are caused by microbes.

Practice

1. What is the key advantage of anaerobic respiration? Suggest some specific situations in which this would benefit organisms in the natural environment.
2. Name a nonalcoholic final product of alcohol fermentation, other than ATP.
3. (a) How many molecules of ethanol are produced by the fermentation of one molecule of glucose?
   (b) How many molecules of carbon dioxide are produced during the fermentation of one molecule of glucose?
   (c) How much oxygen is used during the fermentation of one glucose molecule?

mini Investigation Facultative Microbes

Facultative organisms are those organisms that are able to use either aerobic or anaerobic respiration depending on the environmental conditions in which they are living. Yeast is a good example of this type of organism. In the presence of oxygen, they use aerobic respiration to generate their ATP supplies, in the absence of oxygen they use glycolysis and alcohol fermentation. In this mini investigation you will examine the changes in net gas production associated with a switch from aerobic to anaerobic respiration.

Materials: 3 g Brewers yeast, 50 mL grape juice or apple cider (with no preservatives), 125 mL Erlenmeyer flask, large balloon

- Place 3 g of yeast in the Erlenmeyer flask.
- Add 50 mL of grape juice or apple cider to the flask.
- Allow the yeast to sit for several minutes and then gently stir the mixture to disperse the yeast.
- Cover the flask tightly with the balloon
- Make regular observations over a period of several days documenting changes in the apparent gas volume in the balloon.
- At the end of your experiment, remove the balloon and smell the contents of the flask. Record your observations.
- Display your results using a graphical format.

(a) Were the initial conditions aerobic or anaerobic?
(b) The presence of oxygen gas does not prevent or interfere with the chemical reactions in anaerobic respiration and fermentation pathways. Why then does yeast not continue to follow these pathways when oxygen is present?
(c) During aerobic respiration what gas(es) is produced and consumed? How might this influence the volume of gas in the balloon?
(d) During anaerobic respiration what gas(es) is produced and consumed? How might this influence the volume of gas in the balloon?
(e) Was there evidence of a switch from anaerobic to aerobic or aerobic to anaerobic respiration? Account for these results.
(f) What distinctive odour provided evidence of anaerobic respiration or fermentation?
(g) Suggest modifications to the experimental design that could be used to maintain aerobic conditions over an extended period of time.

EXPLORE an issue

Issue Checklist

- ● Issue
- ○ Design
- ● Analysis
- ● Resolution
- ● Evidence
- ● Evaluation

Aerobic versus Anaerobic Waste Treatment

Human activities produce large amounts of organic wastes. Solid, liquid, and gaseous wastes must be treated to prevent contamination of soil, water, and air. Cities generate enormous volumes of human sewage and household waste (**Figure 4**). Industry and agriculture also produce large volumes of organic waste. Many microbes can use a wide range of organic material as food so they are often used to process waste into less harmful or even valuable compounds. Choosing whether to use an anaerobic or an aerobic microbe to process waste is influenced by many factors.

Figure 4
Garbage collection is a familiar activity in most municipalities.

Understanding the Issue

In a group, use print and Internet resources to research the factors influencing the choice of aerobic and anaerobic systems for a number of the following waste/biomass processing systems:

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- biogas generation
- municipal sewage treatment plant
- household/cottage septic systems
- landfill gas production
- biomass ethanol production

For each system investigate and report on the following:

Raw material(s) – Give a general description of their chemical and physical makeup.

Source of raw materials – Where and why is this material produced in large quantities?

Microbial respiration system(s) – Does the processing of this material involve anaerobic, aerobic, or both forms of respiration/fermentation?

Products – What respiration/fermentation products are produced in this process? Of what value are these products?

Evaluation – Based on your research, is the system an effective way to process waste/biomass? What recommendations would you make to improve or enhance efficient use of this system?

Questions

1. How is oxygen provided in waste treatment systems?
2. How does the presence or absence of oxygen influence the rate of sewage waste processing?
3. Compare, in general terms, the energy content of the final products of aerobic versus anaerobic systems. How can this difference influence the choice of systems and the benefits and uses of such systems?
4. Ethanol is now being used widely as a gasoline fuel additive. What is the main source of this ethanol? What are the benefits of adding ethanol to gasoline?

Lactic Acid Fermentation

Under normal conditions, animals such as humans obtain energy from glucose by aerobic respiration. However, during strenuous exercise, muscle cells demand more ATP energy than can be supplied by aerobic respiration alone. Under such conditions additional ATPs are supplied by lactic acid fermentation, shown in **Figure 5**.

EXTENSION

The Impacts of Lactic Acid Production

Listen to this Audio Clip for an explanation about lactic acid production during a workout and how this lactic acid has both positive and negative impacts on the body.

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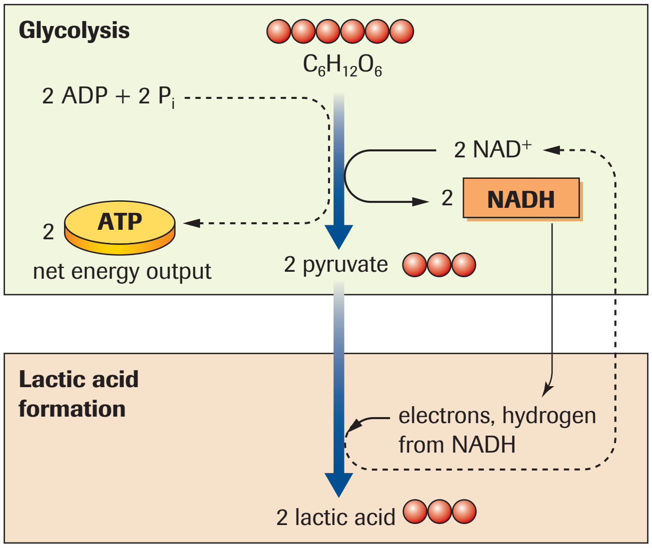

Figure 5
Lactic acid fermentation produces lactic acid from glucose. In the process, NADH is oxidized to NAD^+, allowing glycolysis to continue.

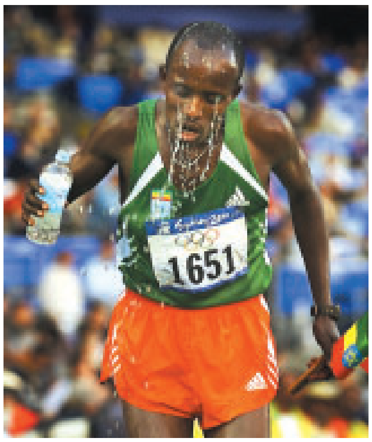

Figure 6
Marathon runners are fatigued after a race because of the accumulation of lactic acid in their muscles. Panting provides the oxygen needed to metabolize the excess lactic acid.

In lactic acid fermentation, NADH produced in glycolysis transfers its hydrogen atoms to pyruvate in the cytoplasm of the cell, regenerating NAD^+ and allowing glycolysis to continue. This results in a change of pyruvate into lactic acid. The overall equation for lactic acid fermentation is

$$\text{glucose } (C_6H_{12}O_6) + 2\text{ ADP} + 2\text{ P}_i \rightarrow 2\text{ lactic acid } (C_3H_6O_3) + 2\text{ ATP}$$

Accumulation of lactic acid molecules in muscle tissue causes stiffness, soreness, and fatigue. Lactic acid is transported through the bloodstream from the muscles to the liver. When vigorous exercise ceases, lactic acid is converted back to pyruvate, which then goes through the remaining stages of aerobic respiration. The extra oxygen required to chemically process this lactic acid (through the aerobic pathway) is referred to as oxygen debt. Panting after bouts of strenuous exercise is the body's way of "paying" the oxygen debt (**Figure 6**, previous page).

Exercise Physiology: VO_2 max and the Lactic Acid Threshold

Exercise physiology is a branch of biology that deals with the body's biological responses to exercise. Scientists in this field try to answer such questions as "Why do muscles become sore and fatigued after a bout of strenuous exercise? How can athletes train to control fatigue and maximize the amount of oxygen that enters their bloodstream? Why does exercise deplete the body of its water reserves and how can athletes avoid dehydration?" Exercise physiologists search for solutions to practical problems faced by individuals who engage in sports and athletic activities. The most common problem faced by athletes is a shortage of energy. Therefore, particular emphasis is placed on the study of aerobic and anaerobic metabolism and its relationship to cardiopulmonary fitness, also known as aerobic fitness. Aerobic fitness is a measure of the ability of the heart, lungs, and bloodstream to supply oxygen to the cells of the body (especially the muscle cells) during physical activity. Aerobic fitness is one of the factors used by physiologists to judge a person's overall physical fitness. Other factors include muscular strength, muscular endurance, flexibility, and body composition (the ratio of fat to bone to muscle).

Since muscle cells need energy from ATP to contract, it is assumed that ATP production (by aerobic respiration) will be increased if more oxygen is absorbed and used by the cells of the body (especially muscle cells) in a given period of time. Exercise physiologists measure a value called the **maximum oxygen consumption (VO_2 max)**, as a measure of a body's capacity to generate the energy required for physical activity. VO_2 max measures the maximum volume of oxygen, in millilitres, that the cells of the body can remove from the bloodstream in one minute per kilogram of body mass while the body experiences maximal exertion. VO_2 max values are typically expressed in mL/kg/min, and are measured directly by a maximal exercise test, also known as a treadmill exercise test. During the test, the person or animal is forced to move faster and faster on a treadmill while expired air is collected and measured by a computer (**Figure 7**). The entire test usually lasts between 10 min and 15 min. Needless to say, the test is not pleasant since one must achieve a rather painful state of maximal exertion. Indirect methods of estimating the value of VO_2 max have been developed that require much less physical strain.

In general, individuals with higher VO_2 max values may be considered more aerobically fit than individuals with lower values.

VO_2 max values vary between 20 mL/kg/min and 90 mL/kg/min. The average value for a typical North American is about 35 mL/kg/min, while elite endurance athletes reach values of 70 mL/kg/min. **Figure 8**, on the next page, shows average VO_2 max values for the athletes of various sports. VO_2 max values may be increased with exercise and training, but genetic variation helps to explain why everyone cannot train to be an elite athlete. Exercising harder, more frequently, and for longer durations will increase VO_2 max values to a degree. However, VO_2 max values also decrease with age. In any case, there is not always a direct correlation between VO_2 max values and overall athletic performance. Although it is true that elite athletes have VO_2 max values that are higher than the population mean, factors such as mental attitude, running efficiency, and the amount of lactic acid produced during exercise greatly influence overall performance.

Since oxygen cannot reach all the body's mitochondria all the time, lactic acid fermentation occurs continuously as you exercise. However, as exercise intensity increases, lactic acid production increases. The lactic acid threshold is the value of exercise intensity at which blood lactic acid concentration begins to increase sharply (**Figure 9**, next page). Exercising at or below this intensity may be sustainable for hours, but exercising

+ EXTENSION

Estimating VO_2 max

In this activity, you will carry out the Rockport Fitness Walking Test. This is a standard test used to estimate the value of VO_2 max. You will walk a distance of 1.6 km on level ground as quickly as possible, without running. You will record how long it took you complete the walk, and measure your heart rate after the walk. You will then substitute these measurements, your age, gender, and mass, into an equation to calculate your VO_2 max.

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maximum oxygen consumption, VO_2 max the maximum volume of oxygen, in millilitres, that the cells of the body can remove from the bloodstream in one minute per kilogram of body mass while the body experiences maximal exertion

Figure 7
A maximal exertion test being conducted in a human performance lab. The apparatus is used to make precise measurements of VO_2 max.

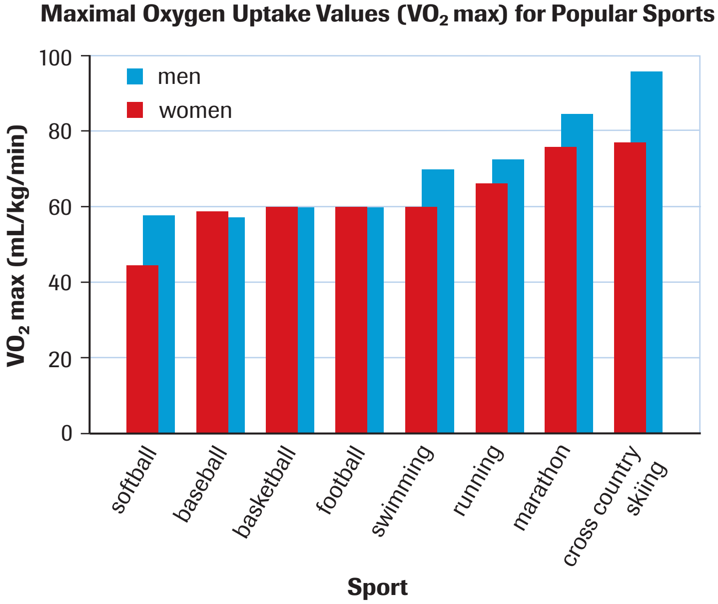

Figure 8
VO_2 max values for athletes in popular sports

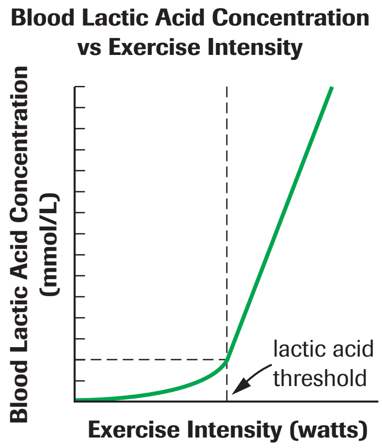

Figure 9
The lactic acid threshold

beyond the lactic acid threshold may limit the duration of the exercise because of increased pain, muscle stiffness, and fatigue.

In general, athletic training improves blood circulation and increases the efficiency of oxygen delivery to the cells of the body. The result is a decrease in lactic acid production at any given exercise intensity level and an increase in the lactic acid threshold. With a higher **lactic acid threshold**, the person will be able to sustain greater exercise intensities and improved athletic performance. One measure of performance is the percentage of VO_2 max at which the lactic acid threshold is reached. Untrained individuals usually reach the lactic acid threshold at about 60 % of VO_2 max. Elite endurance athletes typically reach their lactic acid thresholds at or above 80 % of VO_2 max.

lactic acid threshold the value of exercise intensity at which lactic acid production increases

CAREER CONNECTION

Kinesiologist

Kinesiologists work in the field of human movement, helping people rehabilitate from physical injuries. To be accepted into a kinesiology program, candidates must possess high marks in biology, chemistry, math, and physics. Kinesiologists work in a variety of settings, including hospitals, clinics, and fitness centres. Some large corporations, such as General Motors, hire kinesiologists to advise on ways to improve workers' safety and efficiency on assembly lines—known as ergonomics. Research other career opportunities in the specialized field of ergonomics.

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Practice

4. In addition to ATP, name the other final products of both types of fermentation.
5. How does a human feel the presence of lactic acid in the tissues of the body?
6. Why are VO_2 max values not perfectly correlated with overall athletic performance?

Supplements and Toxins

In addition to our own physical condition and health, environmental factors can have an impact on cellular respiration. Chemicals we ingest or inhale can directly affect cellular respiration pathways in a variety of ways. Some compounds may act as buffers—countering the acidic effects of lactic acid fermentation and potentially enhancing short-term athletic performance. Other chemicals may act as metabolic poisons—inhibiting cellular respiration by interfering with a critical step in a chemical pathway.

Creatine phosphate occurs naturally in the body and in foods. More recently, some high-performance athletes have consumed it as a dietary supplement. Creatine phosphate may serve as a source of energy by donating its phosphate to ADP, thus creating ATP. Some have also hypothesized that increasing the amount of creatine in the diet might increase the concentration of creatine phosphate in muscles. This might increase the availability of high-energy phosphate for ATP and energy production during muscle contraction. Creatine also has the potential to act as a buffer in muscle cells and potentially counter or delay the onset of some of the symptoms associated with lactic acid fermentation.

Many claims have been made regarding the value of creatine supplements. It is said to enhance athletic performance by increasing muscle strength and mass, by providing an instant energy source, and by delaying fatigue. The ultimate benefits and risks associated with its use are not conclusive, however, and potential harmful side-effects are possible. Many medical researchers urge caution and do not recommend its use.

While some chemicals, like creatine phosphate, may enhance respiration under certain conditions, other chemicals have the potential to do quite the opposite. Chemical toxicity can result from a wide range of mechanisms. As you may know, carbon monoxide poisoning is due to this gas's ability to bind to the hemoglobin proteins in your red blood cells. These proteins are responsible for carrying oxygen gas throughout your body. Carbon monoxide competes aggressively for the same binding sites on the hemoglobin molecules. The result is a severe drop in your blood's oxygen-carrying capacity and possible death by asphyxiation. Oxygen is the final electron acceptor that drives the electron transport chain. Without oxygen there is an immediate halt to electron transport and the pumping of hydrogen ions across the inner mitochondrial membrane. Without this activity, H^+ ions are no longer available to drive the formation of ATP—the cell's vital energy source. Cell death follows shortly thereafter.

Rather than limiting the body's access to one of the reactants in cellular respiration, some toxic compounds such as cyanide and hydrogen sulfide directly act on a specific reaction within a respiration pathway.

DID YOU KNOW?

Death and Rigor Mortis

There are two things that happen soon after death: one is a gradual drop in body temperature, and the other is stiffening of the muscles, known as rigor mortis. Rigor mortis is caused not by the drop in body temperature, but by the fermentation of glucose in muscle cells, leading to high levels of lactic acid. The lactic acid causes muscle tissue to become rigid. Rigor mortis sets in much sooner if death occurs immediately following strenuous activity, such as running.

mini Investigation — Metabolic Poisons

Cyanide and hydrogen sulfide are metabolic poisons that enter the environment both from natural sources and as a direct result of human activities. In this mini investigation you will research and document various aspects of the toxicity, sources, and environmental and human health implications of these compounds. Imagine that you are one member of a research team that is preparing a resource binder on environmental toxins.

Using Internet and print resources provide answers and explanations for each of the following and then present them in the form of a two page Fact Sheet that would be suitable for inclusion in the binder.

(a) What stage(s) in cellular respiration are affected by cyanide and hydrogen sulfide?

(b) With what specific compounds do these poisons interfere?

(c) Do these compounds have any commercial value as toxins? Give examples of their use.

(d) Do these compounds occur naturally? If so, where are they found?

(e) What human activities produce these toxins as an industrial pollutant?

(f) How do these toxins impact the health of the environment in the locations in which they occur?

(g) What methods, if any, are used to reduce cyanide and/or hydrogen sulfide pollution?

SUMMARY — Anaerobic Cellular Respiration

- When oxygen is not available, eukaryotes still carry out glycolysis. They recycle the NAD^+ needed for glycolysis by transferring the hydrogen atoms in NADH to pyruvate or acetaldehyde.
- In alcohol fermentation, a molecule of CO_2 is removed from pyruvate, forming a molecule of acetaldehyde. The acetaldehyde is converted to ethanol by attaching hydrogen from NADH.

- In lactic acid fermentation, pyruvate molecules accept the hydrogens from NADHs and form molecules of lactic acid.
- Alcohol fermentation occurs in yeast cells and is used in wine, beer, and bread making.
- Lactic acid fermentation occurs in animal muscle cells during strenuous exercise.
- The maximum oxygen uptake, or VO_2 max, is the maximum volume of oxygen that the cells of the body can remove from the bloodstream in one minute per kilogram of body mass while the body experiences maximal exertion. The lactic acid threshold is the value of exercise intensity at which blood lactic acid concentration begins to increase sharply.
- Chemical toxins, such as carbon monoxide, cyanide, and hydrogen sulfide, can hinder cellular respiration.

Section 7.4 Questions

1. List two differences between aerobic respiration and fermentation.
2. A student regularly runs 3 km each afternoon at a slow, leisurely pace. One day, she runs 1 km as fast as she can. Afterward, she is winded and feels pain in her chest and leg muscles. What is responsible for her symptoms?
3. What role does alcohol fermentation play in the food industry?
4. Compare and contrast the use of anaerobic and aerobic microbes in waste treatment.
5. Define *maximum oxygen consumption*, VO_2 *max*.
6. (a) Determine the value of the lactic acid threshold from **Figure 10**.
   (b) What does this value mean?
7. When Henry Ford built the first Model T in 1908, he expected it to run on pure ethanol produced by fermenting corn. From 1920 to 1924, the Standard Oil Company in Baltimore produced and sold a mixture of ethanol and gasoline called gasohol. However, high corn prices and transportation difficulties terminated the project.
   (a) Research gasohol on the Internet or at the library. List three advantages and three disadvantages of gasohol production in Canada.
   (b) Comment on the viability of a gasohol industry in Canada.

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8. Alcoholic beverages, such as wine and beer, have been produced by humans since the earliest days of agriculture. How do you suppose the process of fermentation was first discovered?

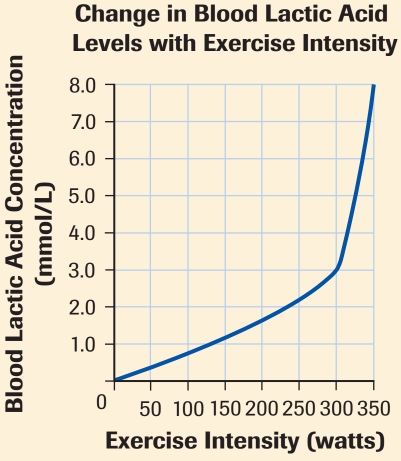

Figure 10

9. Lactic acid fermentation is used in the food industry. Use Internet and print sources to answer the following questions.
   (a) What foods depend on lactic acid fermentation?
   (b) What microbes are used in each food in (a).

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10. Conduct library and/or Internet research to answer the following questions.
    (a) How do long-distance runners make use of the lactic acid threshold in their training?
    (b) What is blood doping? What are the perceived metabolic benefits of this practice? What are some of the dangers associated with blood doping?

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11. Investigate the claim that, historically, Aboriginal athletes were some of the world's greatest long-distance runners.

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INVESTIGATION 7.1

Measuring Oxygen Consumption in Germinating Seeds

When seeds are dormant, they are not actively growing. When the right conditions are met, a dormant seed germinates and begins to grow into a seedling. As growth occurs, cells release the energy stored in cellular compounds such as starch and glucose by breaking them down. The cells then use this energy to fuel their growth. When oxygen is present, energy is released through the process of cellular respiration. The following equation summarizes this process:

$$C_6H_{12}O_6(s) + 6\,O_2(g) \rightarrow 6\,CO_2(g) + 6\,H_2O(l) + \text{energy}$$

glucose + oxygen → carbon dioxide + water + energy

The higher its energy demands, the more quickly a cell will consume both glucose and oxygen. In this investigation, you will compare the energy demands of dormant (dry) seeds and germinating (pre-soaked) seeds by measuring the rates of oxygen consumption using an apparatus called a respirometer.

The respirometer you will use consists of a test tube with a three-hole stopper that holds a thermometer and a straight and a bent piece of glass tubing. When assembly is complete, the respirometer is sealed off from the outside air. The sealed respirometer also contains solid potassium hydroxide (KOH) pellets. KOH reacts with carbon dioxide gas according to the following chemical equation:

$$CO_2(g) + 2\,KOH(s) \rightarrow K_2CO_3(s) + H_2O(l)$$

carbon dioxide + potassium hydroxide → potassium carbonate + water

This reaction with carbon dioxide gas produces a solid (K_2CO_3) and a liquid (H_2O). Therefore, any carbon dioxide gas produced during respiration will not contribute to the volume of gas in the respirometer.

Any change in the volume of gas inside the respirometer will cause the food colouring to move within the bent glass tubing. If gases are consumed, the food colouring will move toward the test tube. The rate of oxygen consumption can be determined by measuring the distance the food colouring moves over time.

The thermometer can be used to determine whether or not actively germinating seeds absorb or release thermal energy.

Report Checklist

○ Purpose	○ Design	● Analysis
○ Problem	○ Materials	● Evaluation
○ Hypothesis	○ Procedure	● Synthesis
● Prediction	● Evidence	

Problems

How does the rate of oxygen consumption by germinating and nongerminating pea seeds vary? Do the activities of germinating seeds absorb or release thermal energy?

Predictions

(a) Predict whether germinating or non-germinating pea seeds will consume more oxygen in 15 min.

(b) Predict whether germinating and/or or non-germinating pea seeds will absorb or release thermal energy

- pea seeds (dry and pre-soaked)
- water
- paper towels
- nonabsorbent cotton
- laboratory scoop or forceps
- potassium hydroxide pellets (KOH)
- petroleum jelly
- liquid food colouring
- tape
- safety goggles
- laboratory apron
- 2 thermometers
- 2 straight glass tubes
- 2 bent glass tubes
- 2 three-hole test-tube stoppers
- 2 large test tubes
- 2 millimetre rulers
- 2 pinch clamps
- 2 pieces of rubber tubing
- 2 test-tube clamps
- 2 retort stands
- medicine dropper

Materials

KOH is highly corrosive.

Avoid any contact with your skin. Wash under cold, running water for 5 min if you get KOH on your skin.

KOH could cause blindness. If KOH comes in contact with your eyes, wash with water for 15 min and seek medical help immediately.

Wear eye protection and a laboratory apron at all times.

Procedure

1. Place 30 dry pea seeds in a large test tube and place a layer of cotton on top of the seeds. Using forceps or a scoop, add approximately 30 KOH pellets on top of the cotton.

INVESTIGATION 7.1 *continued*

2. Assemble the respirometer as shown in **Figure 1**. Attach a millimetre ruler to the end of the bent glass tubing, using tape. Seal all stopper openings with petroleum jelly. Do not add the food colouring or the pinch clamp at this time.

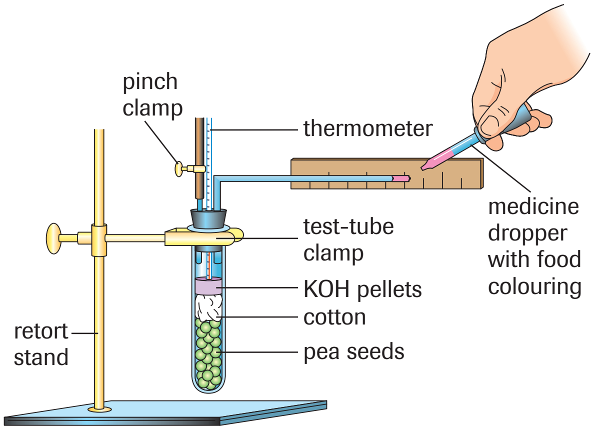

Figure 1
A respirometer

3. Repeat steps 1 and 2 with 30 pre-soaked, germinating pea seeds.
4. Allow both respirometers to stand undisturbed for 5 min.
5. With the medicine dropper, add a few drops of food colouring to the ends of the bent glass tubing.
6. Attach and close a pinch clamp to the rubber tubing on each respirometer.

(c) Record the time at which the pinch clamps were closed. Note the position of the food colouring.

(d) Measure and record the initial temperature in both respirometers.

(e) Record the position of the food colouring and the temperature inside the respirometers every minute for 15 minutes.

Analysis

(f) Graph your data by plotting the distance the food colouring moved on the *y*-axis and the time on the *x*-axis. Plot the data set for both the dry and the pre-soaked peas on the same graph.

(g) Determine the oxygen consumption rates for dry and germinating seeds using the following formula:

$$\text{average } O_2 \text{ consumption rate} = \frac{\text{total distance travelled}}{\text{total time}}$$

(h) Create a graph of temperature versus time. Plot the data for the dry and pre-soaked pea seeds on the same graph.

Evaluation

(i) Evaluate your predictions based on your analysis.

(j) Write hypotheses that explain your findings, referring to the chemical reaction for respiration.

(k) In which direction does the food colouring first move?

(l) What is the purpose of the ruler?

(m) Why was the cotton used?

(n) Explain how the respirometer works.

(o) Why were the openings in the test-tube stopper sealed with petroleum jelly?

(p) What process in the peas caused the food colouring to move into the glass tubing?

(q) How would the results of this experiment differ if KOH had not been added to the test tubes?

(r) What plant process produces oxygen gas? Explain why this process does not affect the results of this experiment.

(s) During respiration, glucose ($C_6H_{12}O_6$) is consumed. What was the source of glucose in the germinating seeds?

(t) Do actively respiring seeds absorb or release thermal energy? Account for this observation based on your understanding of the chemical reactions that occur *during* respiration.

Synthesis

(u) Seeds will not germinate if they are too wet. Why?

(v) Design and conduct an experiment to investigate the effect of temperature on the respiration rate in germinating peas. Be sure to control for the effects of temperature on the volume of gases.

Chapter 7 SUMMARY

Outcomes

Knowledge

- explain, in general terms, how carbohydrates are oxidized by glycolysis and the Krebs cycle to produce reducing power in NADH and $FADH_2$, and chemical potential in ATP, describing where in the cell those processes occur (7.2, 7.3)
- explain, in general terms, how chemiosmosis converts the reducing power of NADH and $FADH_2$ to the chemical potential of ATP, describing where in the mitochondria the process occurs (7.3)
- distinguish, in general terms, among aerobic respiration, anaerobic respiration, and fermentation (7.3, 7.4)
- summarize and explain the role of ATP in cell metabolism (7.1, 7.2, 7.3, 7.4)

STS

- explain that science and technology are developed to meet societal needs and expand human capability (7.4)
- explain that science and technology have consequences for humans and the environment (7.4)

Skills

- ask questions and plan investigations (7.3, 7.4)
- conduct investigations and gather and record data and information by: using experimental methods to demonstrate, quantitatively, the oxygen consumption of germinating seeds (7.3); measuring temperature change over time of germinating and non-germinating seeds (7.3); investigating and integrating, from print and electronic sources, information on the action of metabolic toxins, such as hydrogen sulfide and cyanide, on cellular respiration (7.4)
- analyze data and apply mathematical and conceptual models (7.3, 7.4)
- work as members of a team and apply the skills and conventions of science (all)

Key Terms

7.1

NADH
NAD^+
$FADH_2$
FAD^+
active transport
sodium–potassium pump
aerobic cellular respiration
anaerobic cellular respiration

7.2

glycolysis

7.3

mitochondrion
mitochondrial matrix
intermembrane space
Krebs cycle
oxidative ATP synthesis

7.4

alcohol fermentation
lactic acid fermentation
maximum oxygen consumption, VO_2 max
lactic acid threshold

MAKE a summary

1. Draw a large, well labelled poster summarizing the four stages of cellular respiration. Have the area of the sheet represent the cytoplasm of an animal cell. Draw a very large mitochondrion covering at least one half of the area. Add coloured cartoons representing each stage of the process and place them in their respective locations. Use arrows to indicate the movement of intermediate molecules. Show the ATP yield from each stage and the overall ATP yield from the entire process.
2. Revisit your answers to the Starting Points questions at the start of the chapter. Would you answer the questions differently now? Why?

Go To

www.science.nelson.com GO

The following components are available on the Nelson Web site. Follow the links for *Nelson Biology Alberta 20–30*.

- an interactive Self Quiz for Chapter 7
- additional Diploma Exam-style Review Questions
- Illustrated Glossary
- additional IB-related material

There is more information on the Web site wherever you see the Go icon in the chapter.

UNIT 20 C PERFORMANCE TASK

Student Aquarist

In this Performance Task, you will create an aquatic ecosystem and manipulate its biotic and abiotic factors and monitor the effects these changes have on the metabolic health of the ecosystem's plants and animals. Go to the Unit 20 C Performance Task link on the Nelson Web site to complete this task.

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Chapter 7 REVIEW

Many of these questions are in the style of the Diploma Exam. You will find guidance for writing Diploma Exams in Appendix A5. Science Directing Words used in Diploma Exams are in bold type. Exam study tips and test-taking suggestions are on the Nelson Web site.

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Part 1

Use the following information to answer questions 1 to 3.

Figure 1 is a cut-away diagram of a mitochondrian.

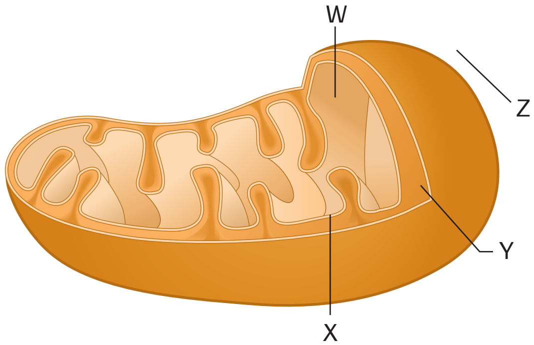

Figure 1

1. The following processes occur in the locations indicated.
   A. glycolysis (W), Krebs cycle (X), electron transport Y)
   B. glycolysis (Y), Krebs cycle (Z), electron transport (X)
   C. glycolysis (Z), Krebs cycle (W), electron transport (X)
   D. glycolysis (Z), Krebs cycle (Y), electron transport (X)

2. In an active mitochondrion the concentration of H^+ ions is greatest at
   A. W
   B. X
   C. Y
   D. Z

3. Imagine that you are able to design an experiment to measure the movement of ATP and ADP molecules within a cell. Which pattern would you expect your results to show?
   A. ATP moves from W to Y; ADP moves from Y to W
   B. ATP moves from W to Z; ADP moves from Z to W
   C. ATP moves from Y to Z; ADP moves from Z to Y
   D. ATP moves from Z to W; ADP moves from W to Z

---

4. Which of the following processes does NOT use ATP as the primary energy source?
   A. active transport
   B. muscle contraction
   C. protein synthesis
   D. osmosis

5. In glycolysis, glucose must first be activated. The activation of glucose requires
   A. two molecules of O_2
   B. two molecules of H_2O
   C. two molecules of ATP
   D. two molecules of NAD

6. Which of the following is involved in the lactic acid fermentation pathway after glycolysis?
   A. production of carbon dioxide
   B. oxidation of NADH
   C. production of ATP
   D. consumption of lactic acid

7. An increased level of aerobic fitness is associated with
   A. a low VO_2 max
   B. a high VO_2 max
   C. a low lactic acid threshold
   D. a high VO_2 max and a low lactic acid threshold

8. NR Each of the following compounds can be used by a cell to produce ATPs. Choose the four compounds that could yield the greatest number of ATPs and place them in order from greatest to least energy. (Record all four digits of your answer.)
   1. pyruvate
   2. NAD^+
   3. $FADH_2$
   4. glucose
   5. NADH
   6. acetyl-CoA
   7. FAD
   8. ADP + P_i

9. NR The complete oxidation of glucose to carbon dioxide and water releases 2870 kJ of energy per mole. Aerobic respiration only captures about 930 kJ of this available energy. Calculate the approximate efficiency of aerobic respiration as a percentage to one decimal place. (Record all four digits of your answer.)

Part 2

10. **Explain** what happens to the rest of the energy in question 9.

11. (a) **Determine** the net gain in ATP when one glucose molecule undergoes aerobic cellular respiration.
    (b) **Determine** the net gain in ATP when one glucose molecule undergoes alcohol fermentation.

12. Name the four stages of aerobic cellular respiration and **describe** where in a cell each stage occurs.

13. Oxygen is the final electron acceptor in the electron transport chain. If it is only needed in the last reaction of this pathway, **explain** how a lack of oxygen causes both the electron transport chain and the Krebs cycle to come to a complete stop.

14. Oxygen is toxic or unavailable to some cells such as yeast. **Summarize** how yeast cells produce ATP from glucose.

Use the following information to answer questions 15 and 16.

Marathon runners have learned that taking walking breaks during a race may get them to the finish line faster than running all the way.

15. DE **Identify** the compound that is more likely to accumulate if the runner does not take any breaks.

16. DE **How** would the walking breaks influence the accumulation of this substance?

17. **Explain** why it is essential that muscle cells convert pyruvate into lactic acid during strenuous exercise, even though the cell obtains very little energy in this process and lactic acid accumulation causes muscle fatigue and pain.

Use the following information to answer questions 18 and 19.

A geneticist gives you two test tubes containing two types of yeast cells that are the same in every way except that one can carry out only aerobic respiration and the other can carry out only anaerobic respiration. The tubes are labelled A and B and they look the same. Yeast from tube A grows rapidly whereas yeast from tube B grows slowly.

18. DE **Identify** the tube that contains the cells that only perform aerobic respiration. **Explain** how you made your choice.

19. DE **Design** two different experiments that could be used to verify your results.

20. DE There is growing interest in the industrial production of ethanol. Sometimes referred to as "green gasoline," ethanol is used as a fuel additive for automobiles. Ethanol use is being encouraged both to reduce dependence on fossil fuels and as a way to reduce greenhouse-gas emissions. While ethanol fuel has promise, many feel that its potential is being over-stated. Use the Internet and other resources to find out more about ethanol fuel. Based on your research, write a unified response addressing the following aspects of the use of ethanol as "green gasoline."

- **Outline** the basic steps in commercial ethanol production. What sources of biomass are available to produce the ethanol and how are these materials processed to produce ethanol?
- **Explain** the potential advantages of replacing petroleum-based fuels with ethanol.
- **Summarize** the energy inputs involved in growing, transporting, and processing these biomass sources. **Explain** how these inputs influence your answer to the previous question.
- **Describe** how scientists are using genetic engineering to improve the efficiency of ethanol production.
- Brazil produces enough ethanol to meet 40 % of its primary energy needs. Does Canada have the same potential for ethanol production? Provide data to **justify** your answer.

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Extension

Use the following information to answer questions 21 to 25.

A 30-year-old, 75 kg male runner completes a marathon in 2 h and 35 min. His oxygen consumption at 15 min intervals is shown in **Table 1**. Oxygen consumption is given by the equation

oxygen consumption (mL/min) = VO_2 max (mL/kg/min) × mass (kg)

Table 1 VO_2 Max Data for Male Runner

Time (min)	VO_2 max (mL/kg/min)	Time (min)	VO_2 max (mL/kg/min)
0	15	150	65
15	40	165	50
30	70	180	45
45	90	195	40
60	90	210	35
75	75	225	30
90	70	240	25
105	65	255	20
120	65	270	15
135	65	290	15

21. DE **Sketch** a graph to display the data in **Table 1**.

22. DE **Identify** the runner's resting VO_2 max.

23. DE **Determine** his oxygen consumption while resting and during his highest VO_2 max.

24. DE **Explain** what is happening during each phase of the graph.

25. DE Use your knowledge of oxygen consumption during exercise to **explain** the oxygen consumption after the race is finished.

Many of these questions are in the style of the Diploma Exam. You will find guidance for writing Diploma Exams in Appendix A5. Science Directing Words used in Diploma Exams are in bold type. Exam study tips and test-taking suggestions are on the Nelson Web site.

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Part 1

Use the following information to answer questions 1 to 3.

The three graphs in **Figure 1** represent energy profiles of chemical processes that occur within cells.

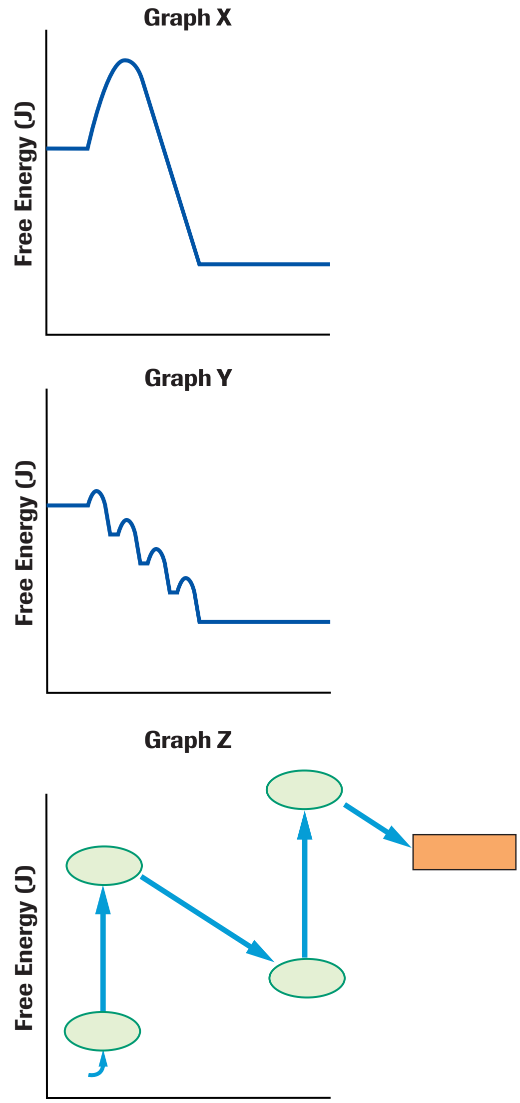

Figure 1

1. The three energy profiles could represent the following processes:
   A. a single reaction (X); the light-dependent reactions (Y); the Krebs cycle (Z)
   B. the electron transport chain (X); glycolysis (Y); the light-dependent reactions (Z)
   C. the Krebs cycle (X); the electron transport chain (Y); glycolysis (Z)
   D. a single reaction (X); the electron transport chain (Y); the light-dependent reactions (Z)

2. The jumps in the energy profile in Graph Z represent
   A. the addition of ATP energy
   B. redox reactions
   C. the absorption of light energy
   D. the action of enzymes

3. In Graph X, the initial increase in energy represents
   A. the energy needed to break bonds
   B. the energy released as bonds form
   C. the energy provided by ATP
   D. an energy increase due to the addition of an enzyme

4. The range of wavelengths of light that is visible to humans is
   A. 380 nm – 550 nm
   B. 400 nm – 600 nm
   C. 380 nm – 750 nm
   D. 200 nm – 900 nm

Use the following information to answer questions 5 and 6.

Figure 2 shows major steps in photosynthesis and cellular respiration, and the molecules that link these two processes.

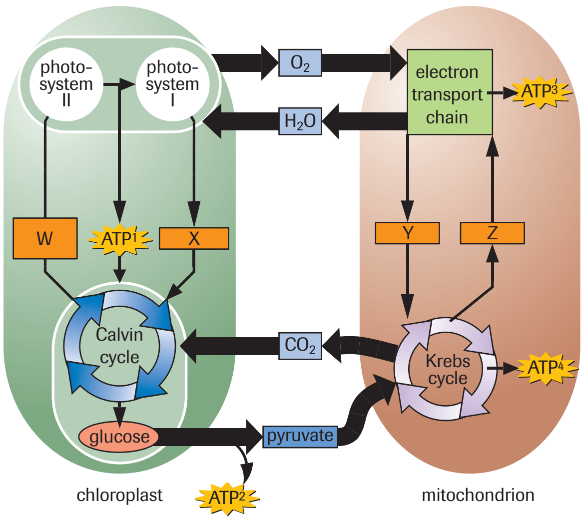

Figure 2

5. Labels W, X, Y, and Z correspond to
   A. H_2O (W); O_2 (X); pyruvate (Y); CO_2 (Z)
   B. O_2 (W); H_2O (X); CO_2 (Y); pyruvate (Z)
   C. O_2 (W); H_2O (X); pyruvate (Y); CO_2 (Z)
   D. CO_2 (W); pyruvate (X); O_2 (Y); H_2O (Z)

6. The ATPs that are of value to the cell for performing cellular functions such as active transport and movement are
   A. all the ATPs
   B. ATP 1 and 2 only
   C. ATP 3 and 4 only
   D. ATP 2, 3, and 4 only

7. NR Choose the steps from the following list that occur in photosynthesis and place them in the order in which they occur in the cell. (Record all four digits of your answer.)
   1. NAD^+ is reduced
   2. H_2O is split
   3. acetyl-CoA forms
   4. CO_2 is produced
   5. CO_2 is fixed
   6. NADPH is oxidized
   7. $FADH_2$ is oxidized
   8. ATP is used

8. NR Using the following formula, calculate the VO_2 max for a 29 year old male with a mass of 80 kg who is able to walk 1.6 km in 8.5 minutes with a final heart rate of 78 beats per minute. (Record your answer to one decimal place.)

VO_2 max (mL/kg/min) =
$132.853 - 0.1696m - 0.3877a + 6.3150g - 3.2649t - 0.1565r$

Part 2

9. **Summarize** what happens during the light-dependent reactions of photosynthesis.

10. **Compare** the general equations of photosynthesis and aerobic respiration. **Outline** the similarities and differences in a table.

Use the following information to answer questions 11 to 13.

Hibernating animals rely on a special kind of tissue called brown fat. This tissue is located around vital internal organs, such as the heart, liver, and kidneys, and releases an unusually large amount of thermal energy when it is metabolically active. This occurs when the animal is "waking up" from hibernation. Researchers have discovered that the mitochondria in this tissue produce a chemical that disrupts the functioning of the electron transport chain, by making the inner membrane permeable to H^+ ions. A drug, dinitrophenol, has the same effect on mitochondria in normal tissues. The drug was prescribed in low doses the 1940s to help obese patients lose weight but its use was discontinued after several patients died.

11. DE **Explain** whether the mitochondria in brown tissue would be able to generate more ATP than the mitochondria in normal tissue.

12. DE **How** would the permeability of the inner membrane to H^+ ions result in additional thermal energy production?

13. DE **Hypothesize** how using dinitrophenol could have caused the deaths.

14. (a) In active muscle tissue, **explain** what happens when the supply of oxygen is not adequate for the demands of oxidative phosphorylation.
    (b) **Why** does deep breathing continue even after strenuous exercise (e.g., running) has stopped?

15. Chemical bonds are forces of attraction that exist between atoms. These forces of attraction vary in their strength. When a chemical reaction occurs, old bonds break and new bonds form as atoms become rearranged. Use this information to **explain** how some reactions require energy while others release energy.

Use the following information to answer questions 16 to 22.

Many people are aware that plants produce oxygen gas—a gas that we need to breathe. This understanding has led to the widespread belief that entire ecosystems such as forested areas are net producers of oxygen. This belief, however, is somewhat misleading. In order for there to be a net production of oxygen gas, photosynthesis must be occurring faster than cellular respiration. The following equations summarize the overall reactions of photosynthesis and respiration:

$6\ CO_2 + 12\ H_2O + \text{solar energy} \rightarrow C_6H_{12}O_6 + 6\ H_2O + 6\ O_2$

$C_6H_{12}O_6 + 6\ O_2 + 36\ ADP + 36\ P_i \rightarrow 6\ CO_2 + 6\ H_2O + 36\ ATP$

16. DE **Identify** the chemical process that produces oxygen gas.

17. DE **Identify** the chemical process that consumes oxygen gas.

18. DE If there were a net production of oxygen gas in an ecosystem, **identify** the chemical that must be accumulating. **Identify** the atmospheric chemical that must be decreasing in concentration.

19. DE **How** would this affect the total biomass of the ecosystem over time?

20. DE **Explain** whether it is possible for such a situation to continue over a very long period of time.

21. DE **Outline** some natural processes that keep biomass from accumulating over time.

22. DE **How** might our understanding of these relationships influence strategies to combat climate change?

23. Review the focusing questions on page 174. Using the knowledge you have gained from this unit, briefly **outline** a response to each of these questions.